PB83-147801

Liner Materials Exposed to Municipal Solid Waste Leachate

Matrecon, Inc.
Oakland, CA

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Dec 82

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
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1. REPORT NO. EPA-600/2-82-097	2.	3. RECIPIENT'S ACCESSION NO. PB83 147801
4. TITLE AND SUBTITLE LINER MATERIALS EXPOSED TO MUNICIPAL SOLID WASTE LEACHATE		5. REPORT DATE December 1982 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) H. E. Haxo, Jr., R. M. White, Paul D. Haxo, and M. A. Fong		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Matrecon, Inc. P. O. Box 24075 Oakland, CA 94623		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO. 68-03-2134
12. SPONSORING AGENCY NAME AND ADDRESS Muncipal Environmental Research Laboratory--Cin, OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, OH 45268		13. TYPE OF REPORT AND PERIOD COVERED Final, 1/1/76 - 1/31/81 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES
See also "Evaluation of Liner Materials Exposed to Leachate", EPA 600/2-76-255, 1976, (NTIS PB-259913), and "Liner Materials Exposed to MSW Leachate", EPA-600/2-79-038, 1979.

16. ABSTRACT

The results of the exposure testing of 65 lining and related materials to MSW leachate for periods of up to 56 months are reported. The materials include 4 admix materials, 2 asphalt membranes, 50 commercial flexible polymeric membranes, and 9 miscellaneous materials, but exclude soils and clays. The principal thrust of the project was to expose 12 primary liners for 12 and 56 months as barrier specimens in 24 landfill simulators loaded with shredded municipal solid waste and determined the effects of the exposures to leachate on their properties and functioning as liners. The primary liners in this study were: four admix materials - paving asphalt concrete, hydraulic asphalt concrete, soil asphalt, and soil cement; two asphaltic membranes - bituminous seal and emulsified asphalt on a nonwoven fabric; six flexible membranes based on the following polymers - butyl rubber, chlorinated polyethylene, chlorosulfonated polyethylene, ethylene propylene rubber, low-density polyethylene, and polyvinyl chloride. In addition, 31 different specimens of membrane liners and 9 miscellaneous related materials were buried in the simulators and tested. The scope of the project was further expanded by the immersion testing of 28 polymeric membranes for up to 31 months at ambient temperature, testing of 14 thermoplastic sheetings for up to 40 weeks in a newly developed pouch test, and testing of the water absorption of 11 membranes for 43 weeks at room temperature and 70°C.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Liners, Linings, Leaching, Refuse disposal, Pollution, Decomposition reactions, Plastics	Solid waste management	

18. DISTRIBUTION STATEMENT Release to public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 188
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA-600/2-82-097
December 1982

PB83-147801

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by

Henry E. Haxo, Jr.
Richard M. White
Paul D. Haxo
Michael A. Fong
Matrecon, Inc.
Oakland, California 94623

Contract No. 68-03-2134

Project Officer

Robert Landreth
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and is a vital communications link between the researcher and the user community.

Though the information presented here is preliminary, it will provide insight into the effects of limited exposure of liner materials to leachate from municipal solid waste. This information could be useful for design purposes if not taken out of context.

Francis T. Mayo, Director
Municipal Environmental Research Laboratory

ABSTRACT

Sixty-five landfill liners and related materials underwent exposure testing to municipal solid waste leachate for periods of up to 56 months. The materials tested include four admix materials, two asphalt membranes, 50 commercial flexible polymeric membranes, and nine miscellaneous materials, but soils and clays were excluded. The principal thrust of the project was to expose 12 primary liners for 12 and 56 months as barrier specimens in 24 landfill simulators loaded with shredded municipal solid waste; determinations were then made as to the effects of exposure on their properties and their ability to function as liners. The primary liners in this study were: four admix materials (paving asphalt concrete, hydraulic asphalt concrete, soil asphalt, and soil cement); two asphaltic membranes (bituminous seal and emulsified asphalt on a nonwoven fabric); and six flexible polymeric membranes (butyl rubber, chlorinated polyethylene, chlorosulfonated polyethylene, ethylene propylene rubber, low-density polyethylene, and polyvinyl chloride).

In addition, 31 different specimens of membrane liners and nine miscellaneous related materials were buried in the simulators and tested. The scope of the project was further expanded by the immersion testing of 28 polymeric membranes for up to 31 months at ambient temperature, testing of 14 thermoplastic sheetings for up to 40 weeks in a newly developed pouch test, and testing of the water absorption of 11 membranes for 43 weeks at room temperature and at 70°C.

The 56 months of exposure to leachate in the landfill simulators did not increase the permeability of any of the liners. The exposure did result, however, in significant losses in the compressive strengths of the admix liners based on asphalt and in softening of the asphaltic membranes. Overall, the polymeric membranes retained their integrity and were only moderately affected by the MSW leachate. Most membranes absorbed leachate to varying degrees but did not deteriorate. Several seams lost strength, but the heat-sealed and bodied-solvent-welded seams retained their strength best.

The partially crystalline thermoplastics (e.g., polyethylene) absorbed the least amount of leachate and retained their properties best. The neoprenes varied considerably, but some swelled and softened. The chlorosulfonated polyethylene and the chlorinated polyethylene materials also swelled and softened. The polyvinyl choride materials swelled slightly and, within the time span of the exposures, retained their original properties. However, signs of plasticizer loss and stiffening had appeared which may be a concern after prolonged exposure. The only polymeric materials that exhibited degradation in this environment were a urethane rubber gasket and, to a smaller extent, an experimental polyester elastomer film.

This report was submitted in fulfillment of Contract 68-03-2134 by Matrecon, Inc., under the sponsorship of the U. S. Environmental Protection Agency. It covers work performed from January 1, 1976 to March 31, 1981.

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(PREVIOUSLY CIN. EPA FORM 387)
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ABBREVIATIONS

ABS	-- acrylonitrile butadiene styrene resin
cm	-- centimetres
COD	-- chemical oxygen demand
CPE	-- chlorinated polyethylene
CSPE	-- chlorosulfonated polyethylene
db	-- dry basis
ELPO	-- elasticized polyolefin
EVA	-- ethylene vinyl acetate interpolymer
EPDM	-- ethylene propylene rubber
g	-- grams
h	-- hour
HDPE	-- high-density polyethylene
Hg	-- mercury
in.	-- inches
ipm	-- inches per minute
LDPE	-- low-density polyethylene
MP	-- megapoise
MPa	-- megapascals
mho	-- micro-mho
mL	-- millilitres
pen	-- penetration
pH	-- hydrogen ion concentration
ppi	-- pounds per inch
ppm	-- parts per million
psi	-- pounds per square inch
PVC	-- polyvinyl chloride
S-100	-- stress at 100% elongation
S-200	-- stress at 200% elongation
SBR	-- styrene butadiene rubber
TVA	-- total volatile acids

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METRIC CONVERSION FACTORS
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To convert	Multiply by
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Feet to metres	x 0.3048
Mils to centimetres (cm)	x 2.54×10^{-3}
Mils to millimetres (mm)	x 2.54×10^{-2}
Pounds per square inch (psi) to megapascals (MPa)	x 6.895×10^{-3}
Pounds per inch (ppi) to kilonewtons per metre (kN/m)	x 1.751×10^{-1}
Pounds (force) to newtons	x 4.448

U. S. Customary Units are used in this report as they are commercially used in the United States in the solid wastes industry as well as the liner production and installation industries.

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ACKNOWLEDGMENTS

The authors wish to thank Robert E. Landreth, U. S. Environmental Protection Agency Project Officer, for his support and guidance in this project. They also wish to acknowledge the guidance of Dr. Clarence Golueke and Stephen Klein of the Sanitary Engineering Research Laboratory, University of California, Berkeley, California, who were responsible for the analyses and characterization of the wastes.

The following companies contributed to this project by supplying samples, information, and technical assistance:

Burke Industries, Inc.
Carlisle Tire and Rubber Company
Cooley, Inc.
Dow Chemical Company
Dynamit Nobel-Harte, Inc.
E. I. du Pont de Nemours and Company
Exxon Chemical Company
Firestone Tire and Rubber Company
Gaco Western, Inc.
B. F. Goodrich Company
Goodyear Tire and Rubber Company
Pantasote Company
Phillips Petroleum Company
Plymouth Rubber Company
Polysar Corporation
Quarry Products, Inc.
Ransome Company
Reeves Bros., Inc.
Ruberoid Building Products, Ltd.
Staff Industries
Union Carbide Company
Watersaver Company
Witco Chemical Corporation

We also gratefully acknowledge the cooperation of the Asphalt Institute and The Portland Cement Association.

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SECTION 1

INTRODUCTION

BACKGROUND

The sanitary landfill is a widely used method for disposal of municipal solid waste (MSW). In many areas, particularly in those areas subject to high humidity and rainfall, leachates generated by water percolating through the landfill can seriously degrade surface and ground waters. Recognizing the potential for pollution, the U. S. Environmental Protection Agency (EPA) sponsored this research project to investigate the ability of various lining materials to control the movement of leachate. Lining landfills with durable materials of very low permeability could provide a long-term solution to the problem of leachate pollution and could also allow sites which were previously unacceptable to be used as landfills.

When this project was initiated in 1973, there was a general lack of knowledge concerning the durability of lining materials in contact with leachate from municipal solid waste landfills. Most experience in the field use of lining materials had been for the impoundment and conveyance of water. Materials used for such purposes included asphaltic materials (in the form of either a concrete or a sprayed-on membrane), soil cement, and compacted soils and clays, including bentonite. The use of polymeric membrane liners for water conservation and conveyance began in the 1940's, with the first membranes used in 1948 for lining canals (Lauritzen, 1967; Dedrick, 1980). These liners were butyl-coated fiberglass. From that time until the initiation of this project, a variety of other membrane materials were developed based on polymers such as polyvinyl chloride (PVC), low-density polyethylene (LDPE), ethylene propylene rubber (EPDM), neoprene (CR), chlorosulfonated polyethylene (CSPE or CSM), and chlorinated polyethylene (CPE). Even after the project was underway, new materials were introduced, e.g., elasticized polyolefin, high-density polyethylene and blends of various polymers.

OBJECTIVES

Work began on this project in March 1973 and continued until March 31, 1981. The scope of work and the project objectives were updated periodically to reflect developments in liner technology and the availability of new materials and information. The following is a cumulative list of the principal objectives of the project:

- To determine the effects of MSW leachate on the physical properties of 12 generic types of lining materials (excluding soils and clays)

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which were considered potentially useful for the lining of sanitary landfills. Leachate generated by water percolating through compacted, shredded municipal solid waste was required.

- To determine how 12- and 24-month exposures to MSW landfill leachate affected the physical properties of the 12 liner materials mounted in the bases of simulated sanitary landfills and the properties of 42 smaller membrane specimens buried in the sand above the mounted liners. The second exposure period was increased to 56 months after the 12-month test values showed only modest effects on the materials.

- To make cost analyses of the use of these materials as sanitary landfill liners. These analyses were to include costs for liner materials and installation, and the benefits from longer durability.

- To estimate the effective life of the 12 liner materials when exposed to prolonged contact with leachate under conditions comparable with those encountered in a sanitary landfill.

- To develop laboratory-scale tests for assessing the permeability and durability of membrane liners under simulated field conditions.

- To generate a useful data base on materials designed to line MSW landfills.

- To determine how various potential lining materials are affected by exposure to MSW landfill leachate for up to 56 months.

- To assess various polymeric membrane liner materials not included in the original scope of work.

This report summarizes the results of the entire project. Progress has been reported in three interim reports (Haxo and White, 1974; Haxo and White, 1976; Haxo et al, 1979) and in four papers presented at the First, Third, Fifth, and Seventh Annual Research Symposia sponsored by the Municipal Environmental Research Laboratory of the U.S. Environmental Protection Agency (Haxo, 1976, 1977, 1979, and Fong and Haxo, 1981). Some of the material has been presented in the EPA Technical Resource Document, Lining of Waste Impoundment and Disposal Facilities (Matrecon, 1980). The last reference covers the state-of-the-art in liner technology as of 1980 and includes the advances in liner technology that have taken place since 1973 when this project was initiated.

The work summarized in this report was primarily an exploratory study concerned with the interaction of liner materials with a representative MSW leachate over a long period of time. Except for a study of seaming, the project did not discuss the design of landfills or the installation of liners, both of which are very important factors in the successful construction and functioning of disposal facilities. All membrane materials were commercial products that had been requested from the liner industry as being suitable for the lining of sanitary landfills. We recognized at the outset of the project that the liner compositions selected and submitted by the industry had not necessarily been used in landfills. However, they represented the state-of-the-art at that time and were all considered potentially effective as linings for MSW landfills. Admix and sprayed-on liners had been used in water containment and conveyance. These test specimens were formulated on the basis of the available technology.

SECTION 2

SCOPE OF WORK

The principal thrust of the project was to investigate the chemical resistance of a number of commercially-available lining materials and other miscellaneous materials to leachate generated from shredded MSW. Consequently, effort was taken to avoid other uncontrollable failures in the liners, e.g., puncture. Twelve primary liner materials were incorporated and exposed as barriers in landfill simulators for 12 and 56 months. These primary liners included:

Four admix materials:

Paving asphalt concrete
Hydraulic asphalt concrete
Soil asphalt
Soil cement

Two asphaltic membranes:

Bituminous seal
Emulsified asphalt on a nonwoven fabric

Six commercially-available flexible polymeric membranes based upon the following polymers:

Butyl rubber
Chlorinated polyethylene (CPE)
Chlorosulfonated polyethylene (CSPE)
Ethylene propylene rubber (EPDM)
Low-density polyethylene (LDPE)
Polyvinyl chloride (PVC)

The primary liner specimens were exposed individually in two sets of 12 specimens each in 24 landfill simulators.

The polymeric specimens along with other materials were also exposed to MSW leachate and related liquids in the following types of exposure:

- Specimens buried in the sand above the membrane liners in the simulators (31 different polymeric membrane sheetings and nine miscellaneous materials).

- Immersion tests of 28 different membrane liner materials in leachate generated in the simulators.

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- Water absorption tests at room temperature and at 70°C.
- Fourteen different thermoplastic membrane liner materials in pouch tests using either leachate from the simulators or a 5% salt solution as the test liquid.

The secondary liner test specimens included membranes of butyl rubber, CPE, CSPE, elasticized polyolefin (ELPO), EPDM, neoprene, polybutylene, polyester elastomer, LDPE, high-density polyethylene (HDPE), and PVC. All the membrane lining materials in the project and the exposure tests performed on each are listed in Section 14.

The nine miscellaneous materials tested in addition to the membrane liners included an asphalt roofing felt, polypropylene, two thermoplastic rubbers, and five commercial gasket materials based on natural rubber, styrene-butadiene rubber, urethane, and two different neoprene compounds. The gasket materials had been considered for use in the construction of the simulators to seal the columns containing the waste to the bases.

The exposure of the liner materials in the simulators ranged up to 56 months, with the bulk of the samples removed at 12 and 56 months. The immersion tests of the membrane liners were run up to 31 months, and the pouch tests were continued up to 36 months on the pouches that did not fail.

An individual simulator in which a single primary liner was exposed consisted of a 10-foot column containing 8 feet of compacted shredded refuse placed on a concrete base. Leachate was generated by percolating 26 inches of tap water per year through the simulator. The quality of the leachate generated in the 24 simulators was in the normal range for leachate generated by full-scale landfills. During the exposure, the average solids content decreased from 3.5%-3.8% to 0.20%. The liners were sealed in the bases with a rapid-set epoxy resin to prevent leachate from bypassing the liners. Thus, whatever seepage occured would be through the liner. Initially, leachate was allowed to pond on the liners until collected every other week. Once leachate began to be collected continuously, a hydraulic head of one-foot was maintained.

Properties of the lining materials were measured in the course of exposure to determine changes. The specimens in the simulators were tested after 12 and 56 months of exposure. The asphaltic membranes were also tested at 43 months. The specimens buried in the sand above these liners were removed and tested at 43 months, and other specimens were buried at that time. The exposed polymeric membrane liners were tested for absorption of leachate and changes in tensile strength, tear resistance, puncture resistance, and seam strength. Appropriate properties of the other materials were tested for change during exposure.

The water permeability of the admixed lining materials was measured in back-pressure permeameters. Permeability values for the polymeric membranes were determined by a variety of methods, principally water vapor transmission and gas permeability. Efforts were made to measure the permeability of the

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polymeric membrane materials to liquids, but, because of their extremely low permeability, reliable values could not be determined.

A test was developed which can be used to assess the relative permeability of membrane liners to water and waste constituents and the effect of exposure to wastes. This test involved sealing a waste into a small pouch made of a given liner material and placing the pouch into a bag containing deionized water. The water in the outer bag was monitored for pH and electrical conductivity. The weight of the test pouch was monitored for changes caused by the permeation of water, ions, and dissolved constituents through the pouch wall. At present, the test is only applicable to thermoplastic membranes which can be heat sealed or seamed with a bodied solvent.

In a single experiment, the effects of exposing a PVC liner to MSW were assessed by recovering samples of the liner from a small demonstration landfill and testing samples of the recovered sheeting in the laboratory.

The costs involving the use of different lining materials were estimated several times during the course of the contract.

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SECTION 3

OBSERVATIONS, CONCLUSIONS, AND RECOMMENDATIONS

When a wide range of polymeric membrane lining materials were exposed to a typical MSW leachate for up to 56 months, only limited changes in properties took place. These results indicate that materials of this type can withstand MSW leachate and be used to line MSW landfills. Only two types of polymeric materials showed significant losses in properties after extended exposure. One, a polyester elastomer, was supplied as an experimental lining material for use in containing oily wastes; the second was a polyurethane which was probably a polyester urethane. The polyurethane had been supplied as a gasket stock for use in the construction of the simulators. Both materials degraded due to hydrolysis.

During the exposure periods, some of the membrane materials exhibited significant swelling and minor losses in tensile and other physical properties but did not increase measurably in permeability. The changes in properties did not seem to become a factor in their functioning as a lining for landfills. Several of the polymeric liner materials swelled more in leachate than in water indicating the importance of the organic components in the leachate with respect to the swelling of polymeric materials.

The effects of immersing polymeric liner materials in leachate were similar to the effects sustained by samples of the same materials exposed as primary liners in the bases of the simulators. Immersion somewhat accelerates the effects of the leachate on the liner materials (i.e., exposure to two sides of a sheeting is more severe than a one-sided exposure). Thus, as immersion testing at various temperatures is commonly used in the rubber and plastics industry to assess performance of composition in potentially aggressive media, immersion in leachate appears to be an effective means of assessing the compatibility and durability of polymeric materials as liners for MSW landfills.

Generic classification of polymeric materials by polymer type is not sufficient to predict the performance of a given membrane. The composition of liners of a given generic type of polymeric material can vary considerably from manufacturer to manufacturer and, to some extent, between the liners of a given manufacturer. Differences in the grade of the polymer itself and differences in the compounding ingredients used affect the performance of a polymeric composition. For instance, specific compounding ingredients may be used to enhance certain properties. Sheetings also differ in the use and type of fabric reinforcement. Note: Because of the proprietary nature of the membranes, few details were known concerning the compositions tested in this project.

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The seaming of thermoplastic membrane liners by heat or by welding with solvents or bodied solvents (which generally are solutions of the liner compound) appeared to yield seams in which the interface between the sheeting was almost eliminated. Variations arising from different levels of workmanship necessitate proper quality controls. Adhesives generally differ in composition from the membrane and thus introduce new components and additional interfaces in the seam assembly. Such assemblies must be assessed as a whole for compatibility with a given waste and for durability under a given set of exposure conditions. The low-temperature vulcanizing adhesives, which are required in the seaming of vulcanized sheetings, generally cure to lower strength values than the sheetings. A significant problem with low-temperature curing adhesives arises in long-term exposures; because of their fewer crosslinks than the vulcanized sheeting, they swell considerably more than the sheeting during exposure and thus can lose strength. Some of the adhesives tested, though weak at the start, did show increased strength with time due to additional crosslinking.

Among the polymeric lining materials, the partially crystalline thermoplastic materials showed the least amount of swell and the smallest change in properties on immersion at normal ambient temperatures. These materials include polyethylenes, polybutylenes, polypropylenes, and thermoplastic elastomers.

The modest effects of the exposures on the polymeric liner materials suggest that the materials themselves are suitably resistant to MSW leachate and that difficulties, if they arise, are more likely to be caused by poor workmanship in the site preparation or in the fabrication, by damage to the liner during installation, or by improper care during the operation of the facility.

The asphaltic materials, whether they are concretes or membranes, exhibited some deficiencies in the exposures to MSW leachate which may ultimately affect their serviceability as linings for MSW waste disposal facilities. The asphalt concretes tended to lose strength which, however, may reflect the choice of aggregate as well as the choice of asphalt. The use of two two-inch lifts of asphalt concrete would reduce the possibility of leakage.

The asphaltic membranes absorbed leachate, and the asphalt component of these materials lost in ductility and elongation. The asphaltic membrane specimens exposed for 56 months had areas that had become "cheesy" and which cracked open when bent. On drying, these areas appeared to return to their original conditions and showed little or no change in basic properties compared with the original asphalt.

The soil cement prepared by standard laboratory method, ASTM D558, yielded a comparatively high permeability to water, i.e., 1.5×10^{-6} cm sec^{-1}. The soil cement compacted in the bases with a pneumatic rammer ranged in permeability from 10^{-5} to 10^{-8} measured on two-inch diameter cores. The soil cement continued to cure and become stronger during exposure. The liner specimens cured the normal 28 days could not be cored; however, the exposed specimens became hard and brittle and thus yielded good cores for testing.

Overall, the results indicate that soil cement is probably not suitable for lining a MSW landfill.

The design of the simulator used in this project appears to be versatile and useful for investigating a wide range of topics including the characteristics of MSW, methane generation, and the use of liners. The simulator is large enough to simulate effectively a landfill containing shredded refuse and to obtain exposure data on liner materials. Nearly replicate performance can be obtained from a set of simulators by proper loading of the shredded refuse. (The compositions of the individual leachates were initially quite uniform. However, in later months when the leachates became less concentrated and the pH's were higher, differences did develop.) The simulator is also small enough to be lifted by a forklift so that the liner specimen can be examined. The simulator can then be returned to operation and the liner exposure continued. The use of a more chemically resistant epoxy resin than the one we used would insure long-term sealing of the liner specimens in the bases and thus avoid the degradation of the seals that took place in several of the simulators.

Only limited data were obtained in EPA Contract 68-03-2824, Field Verification of Liners - Assessment of Long-term Exposed Liner Materials from Municipal Solid Waste Landfills, and these were similar to the data obtained at the Crawford County demonstration landfill with PVC. The results of the verification study include data from liners used in experimental projects and data on a PVC liner used in a sludge pond that was being moved.

Virtually no data exist in the open literature on liner performance in full-scale landfills containing MSW leachate. Such data are needed so that laboratory results can be correlated with field performance. Information on liners for disposal facilities, such as would be developed during the permit process, and information on liner performance should be accumulated for use in developing a correlation with laboratory methods for aid in the selection of materials for liner use. Through such correlation, the liner properties which are most important in predicting the performance of a given polymeric lining material can be determined. As it stands at present, we are not certain which properties correlate significantly with liner performance and which composition factors are truly important. When liners are placed, samples should be retained and provisions made to place some samples in contact with the leachate generated in the landfill. These samples should then be recovered at various times to measure the effects of the exposure. Monitoring of the groundwater below a fill and the development of leak detection devices would also help assess liner performance.

The number of generally accepted specifications for lining materials is limited, and those that are available are incomplete and inadequate for use in the selection of liners for MSW landfills. The liner industry has had a variety of specifications, and each company has its own specifications and selected test methods for its specific materials. ASTM has published specifications for the lining of canals, ponds, and reservoirs. Most of these pertain to polymeric membranes and are primarily designed for water impoundment and conveyance. Specifications for the performance of lining materials in MSW landfills and other disposal facilities need to be established from the standpoint of their compatibility with the waste leachate with which they will be in contact and of their durability under these conditions. Specifications also need to be developed with respect to the seaming of membranes and the installation of liners. Until minimal property values are determined from field experience data, specifications and test methods need to be developed for assuring the quality of a liner material of a generic type and for assuring the quality and uniformity of the specific material placed in the field.

The pouch test should be developed further as a means for evaluating all membrane liner materials for MSW landfills and should include vulcanized sheetings as well as thermoplastic and partially crystalline materials. Vulcanized adhesive systems based on hot vulcanized compounds need to be developed for the vulcanized sheetings. In such systems, vulcanization could be done in a small heated press or by heat-sealing equipment. The principal objective of the test is to assess permeability and durability of the lining material and not to assess seams, except in those cases in which recognized factory or field seam methods are used.

Estimates of the life expectancy of liner materials in a landfill cannot be made based on the data generated in this project. Fifty-six months is too short a time period from which to extrapolate without correlation of various properties with actual performance. The exposures to leachate and water did result in modest losses in properties of the lining materials. However, it is expected that a leveling off of changes will occur in the anaerobic, light-free, and cool conditions at the bottom of a landfill.

Methods should be developed to repair holes in various lining materials, particularly under the adverse conditions of landfill environments. The grout used to repair an asphaltic lining showed no leakage and no saturation after one year of exposure; the repair, however, was made under favorable conditions.

Epoxy resins can be used in landfill-leachate environments if properly selected for moist environments and if the proper mixing ratios of the two parts are observed. The epoxy coating used on the concrete surfaces of the bases of the simulators functioned well with no softening or peeling from the concrete. The cast epoxy rings on the top of the bases were in excellent condition at the end of the 56 months of exposure. The only difficulty encountered was with the rapid set epoxy used to make the seals around the liner specimens. In several simulators, the epoxy seal softened or disintegrated, sometimes completely and sometimes only partially, when two different mixes had been used. Off-ratio mixing was probably the cause of failure.

SECTION 4

TECHNICAL APPROACH

When this project began in 1973, lining MSW landfills to prevent the migration of leachate was a new concept, and little information was available on the effectiveness and the durability of such materials after exposure to leachate generated by the fill over an extended period. The EPA desired to determine the capability and durability in a landfill environment of lining materials that were available at that time by exposure testing a variety of these materials under conditions that simulated actual service conditions as closely as possible. Because of the wide range of materials available, the purpose of such a study was to investigate experimentally lining materials in terms of the generic types such as are listed in Table 1.

In view of the wide variety of materials that were potential candidates for lining landfills and the urgent need for information on the state-of-the-art in terms of the effectiveness of the various materials and their durability in a MSW landfill environment, the following overall approach, which was basically exploratory in nature, evolved during the conduct of the project:

1. To select for exposure testing 12 specific generically different liner materials, excluding soils, from the various types of materials that have been successfully used to line pits, ponds, lagoons, and canals and that appear suitable for lining sanitary landfills. Table 1 presents a list of potentially useful lining materials on the basis of their use in water containment. Cost factors and performance requirements suggested the testing of thin liners. It was felt that thin liners would also accelerate the effects of exposure to leachate.

2. To expose 2 sets of the 12 liner specimens to MSW leachate under pilot scale environments that simulate as closely as possible the conditions a liner would encounter at the bottom of a full-scale operating landfill. The simulated landfills should be designed and constructed so as to ensure anaerobic conditions, and the leachate generated should be representative of the leachate generated in full-scale MSW landfills.

3. To expose specimens of sufficient size to measure the effects of exposure to leachate on selected properties. A typical seam was incorporated in the polymeric membrane liner test specimens to test the strength and durability of seams, which has been a major source of problems and failure in membrane-lined facilities.

TABLE 1. POTENTIAL MATERIALS FOR LINING WASTE STORAGE AND DISPOSAL FACILITIES

Soils and clays:
- Compacted native fine grain soils
- Bentonite, modified bentonite, and other clay sealants

Admix compositions or hard surface compositions:
- Paving asphalt concrete
- Hydraulic asphalt concrete
- Soil asphalt
- Concrete with bituminous seals
- Soil cement with bituminous seals

Sprayed-on liners:
- Liquid rubbers, e.g. polyurethanes
- Catalytically blown asphalt sprayed on soil
- Emulsified asphalt sprayed on soil or on fabric matting
- Asphalt seals

Prefabricated asphalt panels and sheetings

Soil sealants:
- Chemical
- Lime
- Rubber and plastic latexes
- Penetrating polymeric emulsions

Flexible polymeric sheetings:
- Butyl rubber
- Chlorosulfonated polyethylene (CSPE)
- Chlorinated polyethylene (CPE)
- Elasticized polyolefin (ELPO)
- Ethylene propylene rubber (EPDM)
- Polychloroprene (neoprene)
- Polyester elastomer
- Polyethylene (LDPE and HDPE)
- Polyvinyl chloride (PVC)

Chemisorptive liners

4. To subject the liner specimens to appropriate physical and analytical tests for the specific type of liner before and after exposure to MSW leachate. Changes in property values were expected to reflect the performance and durability of the liner in sanitary landfills.

Initially, we planned to test the liner materials after 12 and 24 months of exposure, but because the results of the 12-month exposure showed only modest change, the second exposure period was increased to 56 months.

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The tests shown in Table 2 were used in testing the polymeric membrane liners. All tensile testing was performed in accordance with ASTM D412. It was recognized that fabric-reinforced materials are normally tested in accordance with ASTM D751; however, it was desired that all materials be tested in accordance with the same procedure. The tests of the admix and sprayed-on asphaltic liners are given in Table 3.

TABLE 2. TESTING OF POLYMERIC MEMBRANE LINERS

Thickness.

Tensile strength and elongation at break, ASTM D412.

Hardness, ASTM D2240.

Tear strength, ASTM D624, Die C.

Water absorption or extraction at RT and 70°C, ASTM 570.

Seam strength, in peel and in shear.

Puncture resistance, Fed. Test Method Std. No. 101B, Method 2065.

Water vapor permeability, ASTM E96.

Density and ash of unexposed membranes, ASTM D297.

Volatiles, percent weight loss, 2 h at 105°C.

Extractables, ASTM D3421, modified.

5. Based on the results of the property testing before and after exposure, to assess the performance of the liner specimens and to estimate their respective service lives in a MSW landfill environment.

To make an estimate of service life, it is necessary to determine what constitutes the point of failure of the liner. The function of a liner is to reduce or prevent leakage of leachate out of a landfill. When seepage or leakage through a liner reaches an "unsatisfactory" level, the liner can be considered as having failed. Such failures could arise from:

- Cracking, breaking, or tearing of the liner due to ground settling, rocks, etc.
- Puncturing due to rocks, stumps, plant growth, etc.

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TABLE 3. TESTING OF ASPHALTIC MEMBRANES AND ADMIX LINER MATERIALS

Permeability	Back-pressure permeameter
Density and voids	ASTM D1075 and D2041
Water swell	California Division of Highways 305
Compressive strength	ASTM D1074
Viscosity, sliding plate of asphalts	California Division of Highways 348
Softening point of asphalts	ASTM D2398

- Failure of the seams.

- Disintegration of the liner due to dissolution by or reaction with the leachate.

The ability of the liner material to maintain its integrity in the environment was measured by observing the seepage through the liner and the changes in properties of the materials after exposure to leachate.

We expected some information on the field performance of materials to be supplied by the liner industry but, because this type of information is considered proprietary, little was made available to us.

6. To seal the liner specimens in individual simulated landfills so that whatever seepage occurred could be collected and tested. This required special efforts to avoid leachate bypassing the liner or channeling through the liner, particularly in the cases of soil cement and soil asphalt liners.

7. To create equal conditions in all simulated fills so that valid comparison between liners could be made. This could be accomplished by filling the simulators with well-compacted shredded municipal refuse on a round-robin basis. Compaction, composition, and amount of refuse in all the simulators were to be as close to the same as possible so that leachates of the same concentrations were generated.

8. To determine the composition of the shredded refuse from a blend of grab samples taken during the loading of the cells.

9. After the refuse in the cells is saturated, i.e., brought to "field capacity", to generate leachate by adding one inch of tap water every two weeks (26 inches/year) and allow leachate to pond on the liner at a depth of about one foot.

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10. To monitor the simulator and characterize the leachate regularly during the operating period.

The tests selected for characterizing the leachate were limited to determining temperature, levels of leachate in simulators before collection, amount of leachate collected, total solids, volatile solids, pH, chemical oxygen demand (COD), total volatile acids (as acetic acid), acetic acid, propionic acid, isobutyric acid, butyric acid, isovaleric acid, valeric acid, and caproic acid. These tests were used to assess the uniformity of the leachate among the various simulators, and to measure some of the organic constituents of the leachate. Except for the soil cement, all of the liner materials under test were organic in character, i.e., they were polymeric or asphaltic. It was expected that some of these organic components of the leachate could swell or otherwise deteriorate these liner materials. Of particular interest was the butyric acid, which can degrade many rubber linings used in chemical equipment.

In addition to the six membrane liner materials that were mounted and tested as barriers in the bases of the simulated landfills, 20 other commercial sheetings that had undergone preliminary testing of tensile properties were available for exposure testing. Because these materials differed from the primary test specimens and from each other in origin, thickness, composition, and use of fabric reinforcement, their exposure to leachate could give additional information as to the range of effects related to these differences. Exposure of these secondary test specimens also gave us the opportunity to test various adhesion systems and to determine whether exposure to leachate on both sides of a test specimen would yield the same results as exposure to one side, such as encountered by the primary liner. Consequently, these additional sheetings were buried as 2 x 20 in. coiled strips in the sand above the barrier specimens. Splices were incorporated at one end of most of the strip specimens. The size of these specimens allowed us to perform most of the tests performed on the primary liners, although with fewer test specimens and only in one grain direction.

The similarity of the results from the tests performed on both the buried and the primary specimens after one year in the simulators indicated that the complete immersion of a specimen hung in leachate would be a feasible method for exposing polymeric sheetings in a compatibility study with MSW leachate. The immersion testing would allow for the introduction of more materials into the project and would demand considerably less effort to construct and monitor than the landfill simulators.

The final important goal of the project was to develop test methods specifically to assess membrane liner materials for use in MSW landfills.

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SECTION 5

DESIGN AND CONSTRUCTION OF LANDFILL SIMULATORS

DESIGN REQUIREMENTS

The basic requirement for the design of a landfill simulator is that it simulate as closely as possible actual service conditions that a liner would encounter at the bottom of a typical municipal solid waste landfill. In addition, there were several operational needs to meet so that the effects of long-term exposure to landfill leachate on lining materials could be determined. These operational needs and the environmental conditions in a MSW landfill are discussed in the following sections.

Environmental Service Conditions of Liner in an MSW Landfill

The typical configuration of a liner in service in a MSW landfill is illustrated schematically in Figure 1. The liner is placed upon a properly prepared surface that has been sloped slightly (1-2% grade) for drainage. The amount of surface preparation depends on the specific type of liner material being installed and on the soil base on which the liner is to be placed. Above the liner is a porous soil layer on which refuse is compacted. Leachate generated by water percolating through the refuse is intercepted by the liner, drained through the porous soil layer, and collected for ultimate disposal in a sanitary sewer system, recycled through the landfill to hasten consolidation and stabilization of the fill, or disposed of in another environmentally acceptable manner.

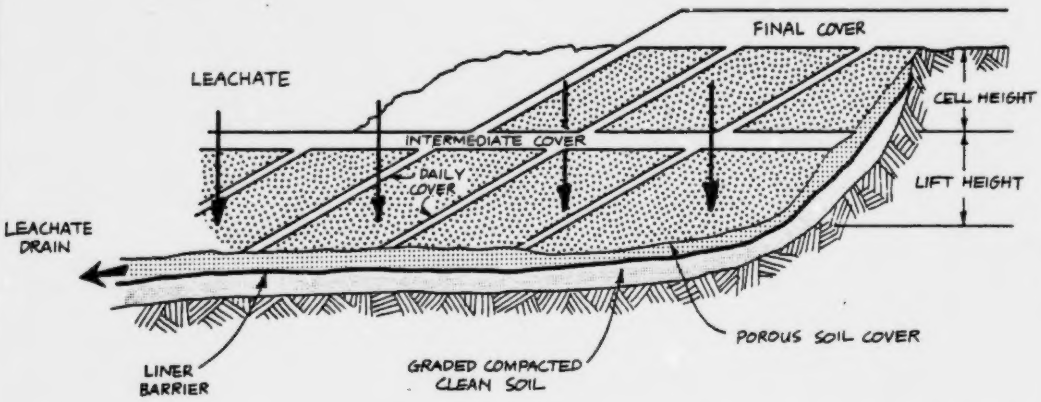

Figure 1. Environment of a liner in service in a sanitary landfill.

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The environmental conditions in which a liner exists ultimately determine how well it can function for long periods of time. Some of the important typical conditions at the bottom of a MSW landfill that can affect the service life of a liner are:

1. An anaerobic environment, i.e. with no free oxygen to cause oxidation of a liner material.
2. Absence of ultraviolet light, which normally degrades many organic materials, e.g., polymers, asphalts, etc. The only time that a landfill liner encounters ultraviolet light is during construction prior to being covered with soil.
3. Humid to wet conditions, particularly if leachate is being generated regularly. The presence of moisture can result in swelling of a liner and, in the case of polymeric membrane liners, leaching of compounding ingredients.
4. Cool temperatures, normally 40 to 70°F. Higher temperatures might be generated within a fill if aerobic decompositon of the refuse is taking place.
5. Moderate acidity of the leachate.
6. High concentration of dissolved salts and ions in the leachate. Many of the ions, depending on their concentrations, can exchange with a clay in a soil and increase the permeability of the soil liner.
7. Dissolved organic constituents in the leachate. Organic solvents and chemicals can swell and degrade asphaltic and polymeric liners and increase permeability of some soils.
8. A moderate hydraulic head pressure. Drainage above the liner in the field should take place continually.
9. Localized strains in the liner when load is placed, due to irregularity of the soil base. A brittle or weak liner might crack and fail under such conditions. Note: As emphasis in this project was related primarily to the effect of MSW leachate on liner materials, we took measures to avoid a failure of this type.

Operational Requirements of Design for Landfill Simulators

In order to determine the effects of long-term exposure in a landfill simulator, the basic requirements of a design for a simulator and a leachate collection system were:

- To be able to monitor the environmental conditions inside the simulators so that there is precise information on the conditions to which the liner specimens were exposed. This included being able to monitor the temperature inside the simulator and the hydraulic head on the barrier, and being able to sample the leachate above the barrier to determine its composition.

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- To be able to measure the amount of leachate that passed through the refuse.

- To be able to measure the amount of leachate that passed through the barrier. To do this meant that the specimens used as barriers had to be large enough to "pass" a measurable amount of leachate.

- To be able to dismantle the cells and recover the exposed liner specimens without damage.

- To have a large enough specimen after exposure to be able to perform the planned series of physical tests.

- To seal the liner specimen in the base of the simulator and have no by-passing of the liner specimens by the leachate generated in the simulator.

DESIGN OF THE SIMULATORS

After consideration of several designs, including a scheme for a single large simulator with a distribution system to bring leachate to individual exposure cells, it was decided to use individual simulators and to mount individual test specimens in each. In order to evaluate the effects of leachate upon the different liner materials being tested and to be able to compare the results, the municipal solid waste loaded into each of the simulators should have the same general composition so that the leachate generated in each of the simulators is essentially of the same quality. In addition, if the project is to be used to study the effects of leachate from a typical MSW landfill, the waste used should be representative of municipal solid waste in the United States. The design selected is illustrated schematically in Figure 2.

An individual simulator consisted of a two-foot diameter steel pipe, ten feet in height, placed on an epoxy-coated concrete base. The liner specimen was sealed into the base with an epoxy adhesive so that leachate could not bypass the liner. Eight feet of shredded solid waste was compacted above the liner specimen. Water percolated through the waste and then pooled on the liner specimen at a depth of one foot. Twenty-four simulators were erected in Building 165 at the Richmond Field Station of the University of California, Berkeley. This site is near the San Francisco Bay and maintains a comparatively uniform temperature. Two specimens of each of the twelve liner materials were mounted in the 24 simulators.

The concrete base featured a horizontal rim on which a liner specimen, 21-22 inches in diameter, could be mounted and sealed into place; it also featured two openings to allow drainage above and below the liner. A cross-section of the interior of the base is presented in Figure 3. The bases were cast individually around a steel mold placed on a wooden form. The irregularities in the interior of the bases were filled with an epoxy resin (Colma-Dur)-sand grout. The interior and the outside top surface of the bases were coated with an epoxy resin (Concresive 1170) to prevent the leachate from migrating out through the concrete and to maintain an essentially gas-tight

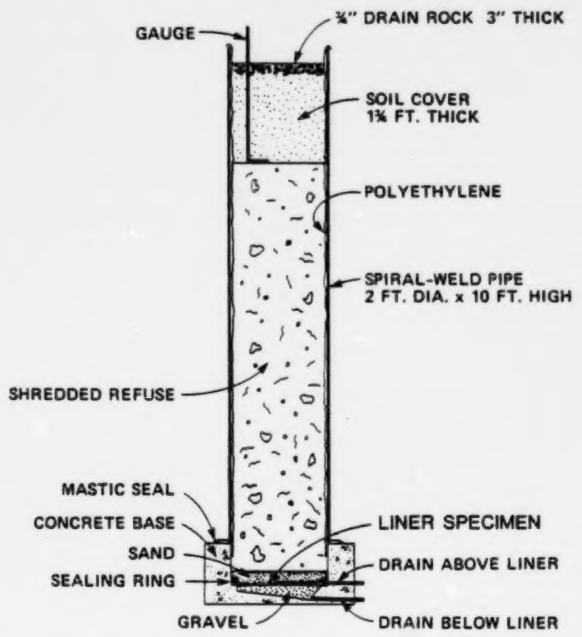
GAUGE
¾" DRAIN ROCK 3" THICK
SOIL COVER
1½ FT. THICK
POLYETHYLENE
SPIRAL-WELD PIPE
2 FT. DIA. x 10 FT. HIGH
SHREDDED REFUSE
MASTIC SEAL
CONCRETE BASE
SAND
SEALING RING
GRAVEL
LINER SPECIMEN
DRAIN ABOVE LINER
DRAIN BELOW LINER

Figure 2. Landfill simulator used to evaluate liner materials exposed to sanitary landfill leachate.

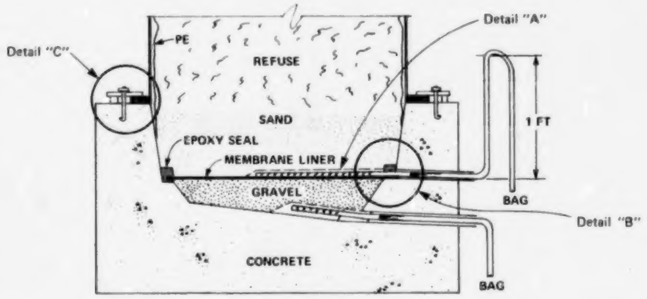
Detail "C"
PE
REFUSE
SAND
EPOXY SEAL
MEMBRANE LINER
GRAVEL
CONCRETE
Detail "A"
1 FT
BAG
Detail "B"
BAG

Figure 3. Base of landfill simulator in which the liner materials were exposed. After a few days of operation, the refuse at the bottom of the column became anaerobic and remained so during the operation of the simulator. The leachate was maintained at a head of one foot by U-tubes. Plastic bags were sealed on both outlets. Strip specimens of membrane liners were buried in the sand for exposure to leachate.

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bowl. In addition, because of the unevenness of the top surface of the concrete bases, a three-inch wide ring of sand-filled epoxy resin was cast to give a smooth mating surface for the flange of the pipe. Each completed base was spark tested and water tested to check for the presence of pinholes in the coating, and recoated or repaired as necessary.

The part of each of the bases below the liner specimens was filled with washed, crushed granite from the Logan quarry in Watsonville, California. It was nominally 1/4 inch x No. 10 (2.0 to 6.3 mm) in size, and was selected because of its high mechanical stability and inertness. Thus it would allow compaction of the soil cement and soil asphalt in the bases. A piece of glass fiber cloth was placed on the rock to reduce the possibility of sharp edges puncturing the membrane liner specimens while the refuse was compacted above the liners.

The specimens were sealed into place by casting a ring of an epoxy resin around their peripheries after they had been placed on the bases. The polymeric membrane specimens were perforated around the outer edge of the specimen, as shown in Figure 4, Detail A. The cast epoxy flowed into these holes to form "pins" to prevent the liner from becoming dislodged, particularly during loading and compacting the refuse in the cells. A rapid-curing epoxy resin (Concresive 1217), mixed with fine gravel, was used in making these rings. Rings were also cast around the edge of the admix specimens compacted in place as well as those compacted outside the bases. Although no annular space existed between the base and those specimens compacted in place, an epoxy ring was cast around the top edge of the specimen to insure a tight seal.

Thin-wall PVC tubes were placed into the two openings in the steel forms when the bases were cast. They served as conduits so that drain pipes could be installed above and below the liner. Acrylonitrile butadiene styrene (ABS) resin pipes were slotted with a hacksaw and installed as drains with the slots facing down. The pipes were covered with a piece of woven glass-fiber cloth to avoid clogging of the slots by the sand placed above the liner specimens. The upper drain pipes were sealed into place in accordance with Details A and B of Figure 4 at the time the liner specimens were sealed into place.

Sand was placed over the liner specimens for drainage of leachate and to protect the specimens from possible damage by sharp objects in the refuse. Four or five of the secondary test specimens were rolled into coils and buried in the sand in each of the bases.

The arrangement of the 24 simulators and the primary liner specimens is shown in Figure 5; information regarding the preparation of the individual admixes and the asphalt membranes is also shown. The first set of simulators, 13-24, was dismantled after 12 months of operation. At 43 months, two columns of waste, 11 and 12, were drained and lifted to inspect and sample the two asphaltic membranes and to recover and test the strip specimens. The columns containing the waste were replaced and the simulators returned to operation for 13 additional months, at which time all of the simulators were dismantled and the specimens were recovered and tested.

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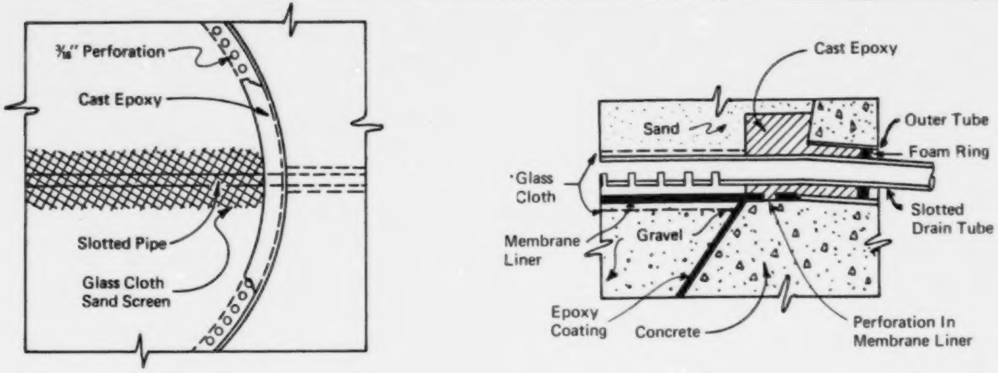
Details of sealing the steel pipes onto the bases are shown in Detail C in Figure 4. The epoxy rings were cast on the surface of the bases in order to make smooth surfaces for mating against the flanges of the pipes. Closed-cell foam gaskets cut from 0.25 inch neoprene foam sheeting were placed between the epoxy ring on the base and the flange. After the refuse had been loaded into the simulators, a bead of mastic seal was placed around the periphery of the flanges.

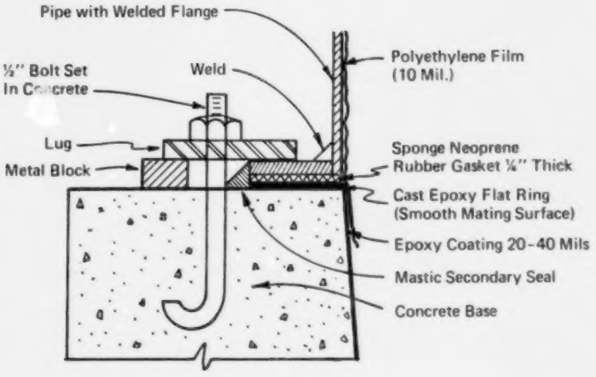

3/16" Perforation
Cast Epoxy
Slotted Pipe
Glass Cloth Sand Screen
Cast Epoxy
Sand
Outer Tube
Foam Ring
Glass Cloth
Slotted Drain Tube
Membrane Liner
Gravel
Epoxy Coating
Concrete
Perforation In Membrane Liner

DETAIL "A"

Epoxy Seal, Membrane Mounted In Base, Drain Tube, As Seen From Above

DETAIL "B"

Cross-Section of Epoxy Seal, Membrane, and Drain Tube


Pipe with Welded Flange
1/2" Bolt Set In Concrete
Weld
Polyethylene Film (10 Mil.)
Lug
Metal Block
Sponge Neoprene Rubber Gasket 1/4" Thick
Cast Epoxy Flat Ring (Smooth Mating Surface)
Epoxy Coating 20-40 Mils
Mastic Secondary Seal
Concrete Base

DETAIL "C"

Attachment, Steel Refuse Cell to Concrete Base

Figure 4. Details of construction and methods of making the various seals to prevent bypassing of the liner specimens by leachate and the entrance of air into the refuse in the simulators.

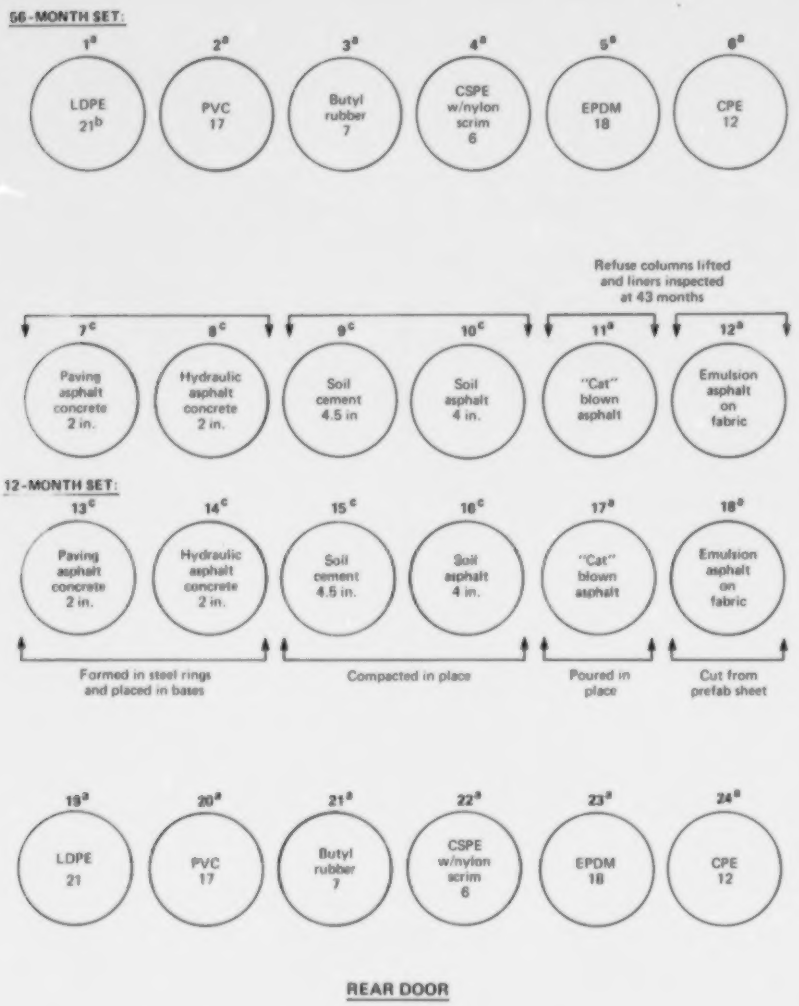

56-MONTH SET:
1[a] LDPE 21[b]
2[a] PVC 17
3[a] Butyl rubber 7
4[a] CSPE w/nylon scrim 6
5[a] EPDM 18
6[a] CPE 12
Refuse columns lifted and liners inspected at 43 months
7[c] Paving asphalt concrete 2 in.
8[c] Hydraulic asphalt concrete 2 in.
9[c] Soil cement 4.5 in
10[c] Soil asphalt 4 in.
11[a] "Cat" blown asphalt
12[a] Emulsion asphalt on fabric
12-MONTH SET:
13[c] Paving asphalt concrete 2 in.
14[c] Hydraulic asphalt concrete 2 in.
15[c] Soil cement 4.5 in.
16[c] Soil asphalt 4 in.
17[a] "Cat" blown asphalt
18[a] Emulsion asphalt on fabric
Formed in steel rings and placed in bases
Compacted in place
Poured in place
Cut from prefab sheet
19[a] LDPE 21
20[a] PVC 17
21[a] Butyl rubber 7
22[a] CSPE w/nylon scrim 6
23[a] EPDM 18
24[a] CPE 12
REAR DOOR

Figure 5. Placement of the liner materials in the MSW landfill simulators. Cell numbers are shown above the circles. Cells containing strip specimens are indicated by (a). Matrecon serial numbers for polymeric membrane liners are indicated in appropriate circles (b). Thicknesses of the asphalt concrete and modified soil liners are also shown in the appropriate circles (c).

The columns of the simulators for containing the refuse were pipes ten-feet high, and two-feet in diameter, made of 12 gauge spiral-weld steel. Three lugs were welded to each of the pipes near the top to aid in lifting and placing them on the bases. The bottom of each pipe had a two-inch flange of 0.25-inch thick steel. A low-density polyethylene (LDPE) sleeve which extended below the flange and folded over the top edges of the pipe was used to line the pipes to prevent rusting of the pipes from contaminating the leachate. The sleeve was tacked to the pipe with a contact cement at the bottom. LDPE was chosen over an epoxy resin coating because of its lower cost and its acknowledged inertness to degradation.

A platform was erected around the columns to furnish a walkway and working surface at 2.5 feet below the tops of the simulators. The simulators were then filled with compacted refuse up to approximately two feet below the top edge. A two-foot gauge-stick with a foot was placed on top of the refuse to monitor how much the refuse settled in the simulators. A one and three-quarter foot cover of screened topsoil and a three-inch layer of 3/4-inch drain rock were placed above the refuse. The procedure followed in the filling of the simulators is described in Section 7.

Two iron constantan thermocouples were placed in each of four of the simulators to determine the temperature in the simulators and duration of aerobic conditions, which result in elevated temperatures. One was installed in the bases before the simulators were filled so that the thermocouple lay directly on the membrane about four inches in from the edge. The lead inside the base was covered with 1/8 in. plastic tubing. The other end of the lead was brought up under the gasket. The end of the tubing with the couple was sealed with epoxy to prevent leachate from seeping out. The second thermocouple was installed 12 in. above the pipe flanges after the simulators were filled. The end of the couple was sealed into a thin wall brass tube which extended 12 in. into the compacted waste.

LEACHATE COLLECTION SYSTEM

The initial system devised to collect leachate intermittently above and continuously below the liners is shown in Figure 6. This system maintained the anaerobic conditions within the simulators. It featured:

1. Plastic bags with two outlets. Initially, the bags were made of 5 mil LDPE, but later were made of 10 mil polybutylene because the LDPE bags that we fabricated failed at the seams when filled with leachate. The capacity of the bags was about 2.5 gallons.
2. A valve on the outlet of the drain pipe from above the liner. This was kept closed except at the time of draining the leachate.
3. The drain from below the liner was kept closed unless leachate passed though the liners, at which time a smaller plastic bag, similar to those discussed above, was mounted and the leachate allowed to drain continuously.
4. A standpipe on four of the simulators, i.e., one per row of columns. The standpipes indicated the level of leachate in the simulators.

The initial drain system did not function well because it allowed the head of leachate to vary from simulator to simulator, because drainage was slow, and because leachate accumulated in the columns. U-tubes were then installed in the system, as shown in Figure 3, so that a head of one foot of leachate remained on the specimens when the simulators were allowed to drain continuously.

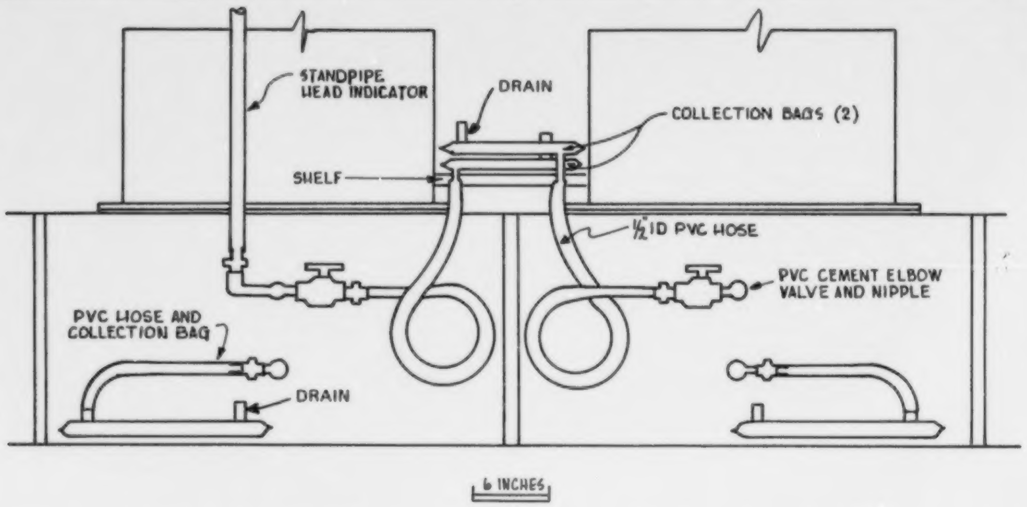

STANDPIPE HEAD INDICATOR
DRAIN
COLLECTION BAGS (2)
SHELF
1/2" ID PVC HOSE
PVC CEMENT ELBOW VALVE AND NIPPLE
PVC HOSE AND COLLECTION BAG
DRAIN
6 INCHES

Figure 6. Leachate collection system designed to prevent air from entering the simulators and to prevent exposure of leachate to air during the collection and weighing.

Towards the end of their operation, the simulators began producing methane. Gas vents had to be added to the drain system as shown in Figure 7 to prevent the collection bags from bursting. The vents included a water seal which prevented air from entering the bag and oxidizing the leachate.

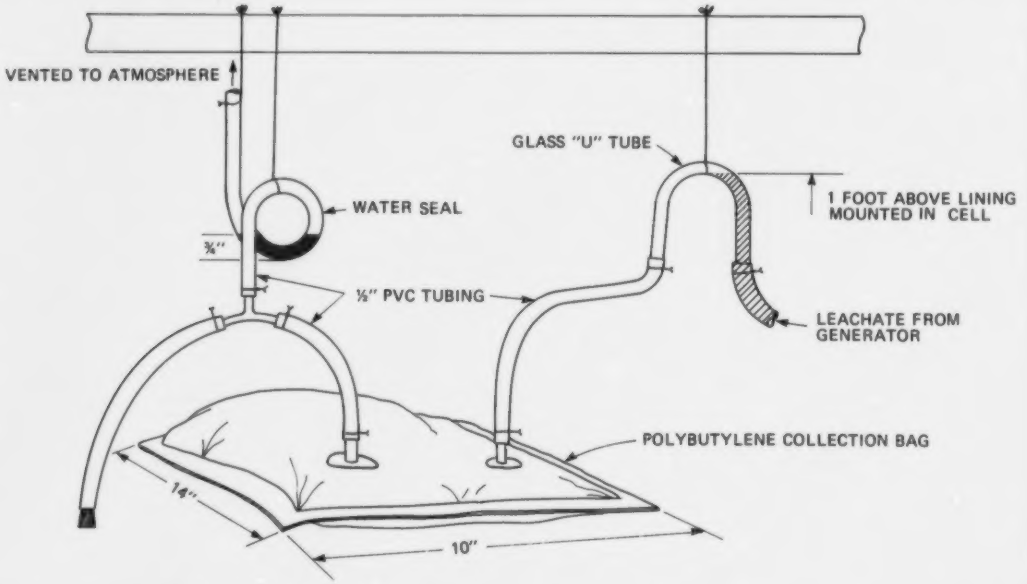

VENTED TO ATMOSPHERE
WATER SEAL
3/4"
1/2" PVC TUBING
GLASS "U" TUBE
1 FOOT ABOVE LINING MOUNTED IN CELL
LEACHATE FROM GENERATOR
POLYBUTYLENE COLLECTION BAG
14"
10"

Figure 7. Leachate collection bag with water seal and vent to prevent excessive gas pressure build-up in the bag.

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SECTION 6

SELECTION OF LINER MATERIALS FOR EXPOSURE

The selection of the specific liner materials for exposure testing involved two major steps:

1. Selecting the types of membranes and admix materials from the broad range of materials available.

2. Selecting specific materials, compositions, and sheetings of the selected types.

As soils and clays were being tested in other studies (Farquhar and Rovers, 1976; Fuller and Korte, 1976; Griffin and Shimp, 1976), EPA specifically excluded them from this study.

Excluding soils, there were three basic types of materials that have low permeability and appeared potentially useful in the lining of landfills:

1. Flexible polymeric membranes.
2. Admixes of various types
3. Sprayed-on membranes.

In this section we discuss the candidate liner materials that were available in 1973 and present the guidelines followed in the selection of the 12 specific materials used as barriers in the simulators, i.e. the primary materials. We also discuss some materials which became available since the initiation of the program and the selection of the specimens of flexible membranes for:

1. Exposure testing as strip specimens buried in the sand layer placed above the membrane-type primary liners.

2. Immersion testing in leachate generated in the simulators.

3 Testing as pouches filled with leachate or 5% salt solution.

In all, 46 different materials were tested in this program over the more than seven years that it was conducted. Four of the materials were admixes, two were sprayed-on asphaltic membranes, and the remaining 40 were flexible membrane liners of various types.

GUIDELINES USED IN THE SELECTION OF LINER MATERIALS FOR STUDY

The primary thrust of this study was to determine the chemical resistance of 12 selected liner materials to MSW leachate by exposing these materials under conditions that simulated the environment of a liner in a typical MSW landfill.

In selecting the 12 primary test materials, we used the following guidelines:

1. To test as wide a range of generic materials of low permeability as possible, but excluding native soils and clays.
2. To include state-of-the-art lining materials that were commercially available in 1973 and had been successfully used as barriers to prevent seepage of water from pits, ponds, lagoons, or canals.
3. In the case of the admixes, to design materials of low permeability.
4. To select types of materials that can be expected to resist change in permeability and physical properties when exposed to leachate in landfill environments.
5. To select materials that are compatible with landfill construction and operations.
6. To select materials that are economical and can be installed by accepted techniques and procedures.

As a basis for selecting specific materials to be tested in the primary exposure, we considered the following additional guidelines:

1. Whenever possible, to select polymeric membranes of 30 mil thickness so that thickness did not become a factor when comparing the permeability results.
2. To select a polymeric membrane of a given generic type which had a good set of physical properties based upon screening tests.
3. To test only unsupported flexible membranes, i.e. without fabric reinforcement. Note: In the case of CSPE a fabric reinforced sheeting was selected because the available membranes of CSPE were fabric reinforced.
4. To select thicknesses of the non-membrane liners which were typical of the thickness of the respective type of liner as it was constructed in the field.

Samples of membrane liners that were considered suitable for use in the lining of MSW landfills were requested from the liner industry for use in this study. Consequently, the first step in the selection of specific materials was made by manufacturers or suppliers.

FLEXIBLE POLYMERIC MEMBRANE LINERS

Polymeric membrane liner materials are of particular interest for the lining of waste disposal sites because of their low permeability. Synthetic polymers are used in a wide range of products and vary considerably in chemical and physical properties. However, a polymer is rarely used alone in a product; it is usually compounded with a variety of ingredients, e.g., fillers, plasticizers or oils, antidegradants, and curatives, to improve selected properties or the balance of properties depending on end-use and to reduce cost. Sheetings can be produced by calendering, extrusion, or coating processes, either as an unsupported film or as a sheeting with fabric reinforcement to increase tear strength. As manufactured, sheetings are narrow and are usually seamed in a factory to make large panels that are transported to the impoundment or disposal site where they are assembled to form the completed liner.

The following steps which are performed by one or more organizations, are involved in the preparation and installation of polymeric membrane liners:

1. Production of the polymer.
2. Compounding of the polymer and manufacture of the polymeric sheeting.
3. Fabrication of panels in a factory.
4. Installation of the liners in the field.

Membranes of a given generic polymer type produced by different manufacturers can differ considerably in composition depending on the compound formulation. This is also true to some extent of membranes produced by one manufacturer. Because polymers of a given generic type vary in grade and in source, differences between membranes can also arise from the polymer itself. Successful use in some environments may require very specific compounding.

All liner samples tested in this project were commercial or developmental materials supplied by their manufacturers. None of the compositions were known except in general terms because of the proprietary nature of the compositions. In requesting the samples, the purpose of their use in the project was indicated, and we assumed that the materials were selected to meet the basic requirements for lining landfills or for service in a landfill environment.

Each type of polymeric material that was tested is described and discussed individually in the following subsections. The discussions include those materials available at the time the project began in 1973 and those materials that became available during the course of the project. The results of testing the properties of these materials before exposure to leachate are presented in Appendix A.

Butyl Rubber

Butyl rubber is a copolymer of isobutylene (97%) and a small amount of isoprene introduced in the polymer chain to furnish sites for vulcanization (crosslinking). Properties of butyl rubber that relate to its use as a liner are:

- Low gas and water vapor permeability.
- Thermal stability.
- Ozone and weathering resistance.
- Chemical and moisture resistance.
- Resistance to animal and vegetable oils and fats.

Butyl rubber is compounded with fillers and oil and generally vulcanized with sulfur. Butyl vulcanizates are highly swollen by hydrocarbon solvents and petroleum oils, but are only slightly affected by oxygenated solvents and other polar liquids. Butyl also has a high resistance to mineral acids, a high tolerance for extremes in temperature, and retains its flexibility throughout its service life.

Liners of butyl rubber were among the first synthetic liners to be used (Dedrick, 1980; Lauritzen, 1967; Smith, 1980). As of 1973, butyl rubber liners had been in service for about 25 years in water impoundments. In outdoor exposure in water management use, butyl rubber sheetings have generally shown little or no degradation after 20 years of service.

Butyl rubber sheetings used as liners were available in 1973 in either unsupported or fabric-reinforced versions of 30 to 125 mils in thickness. These sheetings are generally seamed with two-part, low temperature curing adhesives which may be less resistant to the service conditions than the liner itself.

We had originally planned to test an unreinforced butyl sheeting of 30 mil thickness as a primary liner, but we were unable to locate any of that thickness; we then selected an unsupported sheeting, 60 to 65 mils in thickness. The seam across the center of the primary specimen was prepared with a two-part, low-temperature curing adhesive used in conjunction with a gum tape, both of which were supplied by the liner manufacturer. Specimens of the same butyl sheeting were also buried in the simulators along with specimens of two other butyl sheetings of 60 and 90 mils thickness. A fourth butyl rubber sheeting of 62 mil thickness became available and was tested in the immersion study. No butyl rubber sheeting was tested in pouch form because of the difficulty in making butyl pouches with narrow durable seams.

Chlorinated Polyethylene (CPE)

Chlorinated polyethylenes form a family of flexible thermoplastic polymers produced by chlorinating high density polyethylene; CPE can be crosslinked with peroxides, but in liner compositions, it is generally used as a thermoplastic. It is compounded with fillers, such as carbon black and inorganic fillers, and with oil. Note: In recent compounding practice, polyvinyl chloride or CSPE are sometimes added to improve tensile and thermal properties.

Most CPE compositions withstand ozone, weathering, and ultraviolet light, and resist many corrosive chemicals, hydrocarbons, microbiological attack and burning. Also, some compounds of CPE are serviceable at low temperatures and are nonvolatile. As of 1973, sheetings of CPE had been used as linings for waste, water, or chemical storage pits, ponds, or reservoirs.

The CPE membrane selected for the primary exposure test was an unsupported thermoplastic sheeting 31 mils in thickness. The seam across the center of the specimen was prepared with a 50:50 solvent mixture of toluene and tetrahydrofuran (THF). Samples of the same CPE material were also exposed as buried strips and in small slabs in the immersion test. In addition to the primary CPE liners, four additional different CPE sheetings were exposed in the study. All were unsupported. Two were buried in the simulators, and the other two were immersed in leachate. Two were fabricated into pouches and tested with leachate or 5% salt solution.

Chlorosulfonated Polyethylene (CSPE)

Chlorosulfonated polyethylene is a family of saturated (no double bonds in the polymer chain) polymers prepared by treating polyethylene in solution with a mixture of chlorine and sulfur dioxide. These polymers contain from 25-43% chlorine and from 1.0-1.4% sulfur and can be used in both thermoplastic (uncrosslinked) and in vulcanized (crosslinked) compositions.

Most CSPE compositions are characterized by ozone resistance, light stability, heat resistance, good weatherability, and resistance to deterioration by corrosive chemicals, e.g., acids and alkalies. They have good resistance to growth of mold, mildew, fungus, and bacteria, but only moderate resistance to oil. Membrane liners based on this polymer are available in both vulcanized and thermoplastic forms, but primarily in the latter. The thermoplastic versions slowly crosslink on exposure to moisture and the weather after placement. Usually CSPE sheetings are reinforced with a polyester or nylon scrim. They generally contain at least 45% of CSPE polymer by weight (Burke, 1979; DuPont a,b). The fabric reinforcement gives needed tear strength to the sheeting for use on slopes, and reduces the distortion resulting from shrinkage when placed on the base and when exposed to the heat of the sun.

CSPE membranes can be seamed by heat sealing, dielectric heat sealing, solvent welding, or by using a "bodied" solvent adhesive. As of 1973, they had been used to line pits, ponds, and lagoons, and also to impound highly acid-contaminated fluids. After PVC membranes, CSPE membranes are the most widely used of the polymeric flexible liner materials.

We had originally planned to exposure test only nonreinforced sheeting, but no nonreinforced CSPE sheeting was available at that time in the quantity desired. Consequently, the CSPE sheeting that was selected as a primary liner was 34 to 36 mils in thickness and reinforced with a nylon scrim with a thread count of 8 x 8 per inch. Nylon can be highly affected by strongly acidic conditions. We incorporated a two-inch lap seam in each of the mounted specimens using the manufacturer's adhesive, which was basically a bodied solvent, and following his procedure.

Specimens of the same CSPE sheeting were also exposed as buried coiled strips in the simulators, as small test slabs in the immersion tanks, and as pouches containing either leachate or 5% salt solution. Four other CSPE sheetings were also tested; two of these were unsupported and two were fabric reinforced. Of the four additional materials, two were buried in the simulators, two were immersed in leachate, and one, an unsupported sheeting, was fabricated into a pouch, which was tested with MSW leachate from the simulators.

Elasticized Polyolefin (ELPO)

Elasticized polyolefin is a blend of rubbery and crystalline polyolefins. This polymeric material was introduced in 1975 as a black unvulcanized, thermoplastic liner, which is heat sealable with a specially designed heat welder in the field or at the factory. It has a low density (0.92) and is relatively resistant to weathering, alkalies, and acids (Haxo and White, 1977). It is manufactured by blow extrusion and is supplied as unsupported sheeting 20 mils thick, 20 feet wide, and up to 200 feet long which is shipped to site for assembly on the field.

Samples of the sheeting were buried for one year in a simulator that had been opened to inspect the liner about one year before the final dismantling of the simulator. Samples were also immersion tested in leachate and tested in the pouch test with MSW leachate and with salt solution.

Ethylene Propylene Rubber (EPDM)

EPDM is a terpolymer of ethylene, propylene, and a diene monomer that introduces a small number of double bonds which are sites for vulcanization of the rubber. The unsaturation is in the side chains of the polymer and not in the main chain, as in the case of butyl rubber. Such a location of unsaturation imparts good ozone, chemical, and aging resistance to the rubber.

Note: EPDM is chemically similar to, and can be covulcanized with, butyl rubber; consequently, it is now added to butyl rubber liner compounds to improve the resistance to oxidation, ozone, and weathering.

As it is a wholly hydrocarbon rubber like butyl, EPDM when properly compounded has excellent resistance to water absorption and permeation but has relatively poor resistance to hydrocarbons. EPDM sheeting is available in 54-inch widths and 20 to 60 mil thickness, in both unsupported and fabric-reinforced versions. Special attention is required in seaming this material, because low-temperature vulcanizing adhesives generally need to be used.

The specific membrane of EPDM that was selected for the primary exposure test was vulcanized and unsupported; as it was not available in 30 mil thickness, the membrane selected had a thickness ranging from 49 to 53 mils and came supplied with factory-made seams.

Specimens of the same EPDM sheeting were also exposed as coiled strips in the simulators and as small slabs in the leachate immersion tanks. Five additional EPDM sheetings were also tested, one of which was unvulcanized and fabric-reinforced. Of the five, two were exposed as buried specimens and four were exposed to MSW leachate in the immersion tanks. None was tested as pouches because of the difficulty in making narrow seams based upon low-temperature vulcanizable adhesives.

Neoprene

Neoprene is the generic name of synthetic rubbers based upon chloroprene. These rubbers are vulcanizable, usually with metal oxides, but also with sulfur. They closely parallel natural rubber in mechanical properties, e.g., flexibility and strength. However, neoprene compositions are generally superior to natural rubber compositions in their resistance to oils, weathering, ozone, and ultraviolet radiation. Most neoprene sheetings are relatively resistant to puncture, abrasion, and mechanical damage. Neoprene membranes have been used primarily for the containment of wastewater and other liquids containing traces of hydrocarbons. They also give satisfactory service with certain combinations of oils and acids for which other materials do not provide long-term performance (Kumar and Jedlicka, 1973; Lee, 1974).

Neoprene sheeting for liners is vulcanized and seaming is relatively difficult because vulcanizing cements and adhesives must be used.

Neoprene sheeting was not selected as a primary liner, principally because of its relatively high cost, but also because of the sensitivity of the sheetings available to prolonged exposure to water. However, five different neoprene sheetings were tested in the project, one of which was buried in a simulator for one year. A neoprene sheeting was also fabricated into a pouch, which was tested with leachate. Samples of four other neoprene sheetings were immersion tested in the MSW leachate.

Polybutylene

This polybutylene is a high molecular weight polymer synthesized from butene-1. The version of polybutylene used in this project was specifically designed for blown film extrusion. Films of this material feature good flexibility, heat sealability, low moisture vapor transmission, and good creep resistance.

Polybutylene is available in thin films, principally for use as packaging. It has not been manufactured for use as a liner material. Because of its low creep and the excellent quality of its heat-sealed seams, we used a polybutylene film of 10 mil thickness to replace polyethylene to make the leachate collection bags. We also exposure tested this film as buried specimens in the simulators (for one year), as small slabs in the immersion tanks, and as pouches filled with leachate.

Polyester Elastomer

This polymer is a thermoplastic polyester elastomer film which was introduced as a noncommercial, experimental liner material because of the polymer's good resistance to oils and its heat sealability. We tested a film of this polymer of 7-10 mils thickness in the leachate immersion and in the pouch tests with leachate and with 5% salt solution.

Polyethylene

Polyethylene is a thermoplastic, partially crystalline polymer based upon ethylene. It is made in two major types: (1) low-density polyethylene (LDPE), and (2) high-density polyethylene (HDPE). The properties of a polyethylene are largely dependent upon its crystallinity and density. HDPE polymers exhibit superior resistance to oils, solvents, and permeation by water vapor and gases. Unprotected clear polyethylene degrades readily on outdoor exposure, but the addition of 2%-3% of fine particle size carbon black can protect the polymer against ultraviolet light. Polyethylene sheetings, for the most part, are free of other additives such as plasticizers and fillers. There are slight variations in the composition of HDPE sheetings due to compounding differences among the manufacturers.

Both types of polyethylene have been used as liners. As of 1973, unsupported membranes of LDPE had been used for 15 to 20 years (Hickey, 1969) in lining canals and ponds. The LDPE available in thin sheeting tends to be difficult to handle and to field seam. Also, it punctures easily under impact such as when rocks are dropped on the lining.

A low-density polyethylene, nonpigmented film of 10-12 mils thickness was selected as a primary liner material and was also tested as buried specimens in the simulators, in leachate immersion, and in pouches containing MSW leachate. The same material was used to line the steel pipes of the simulators and to make the original leachate collection bags. The LDPE bags, however, were replaced with polybutylene bags when continuous collection of leachate was started. The LDPE bags broke at the seams when they became full.

Linings of HDPE introduced commercially toward the end of the project were available in sheets 30 to 125 mils in thickness; special seaming equipment has been developed by the suppliers for making seams both in the factory and in the field. This type of liner is very stiff compared to most of the other membranes described. A single strip of HDPE of 95 mils thickness was buried for one year in one of the simulators that was opened to inspect the primary liner in-place.

Polyvinyl Chloride (PVC)

Polyvinyl chloride is produced by any of several polymerization processes from vinyl chloride monomer (VCM). It is a versatile thermoplastic polymer which is compounded with plasticizers and other modifiers to produce a wide range of physical properties. PVC sheetings can be readily seamed with bodied solvents or by heat or dielectric methods.

PVC liners are produced in roll form in various widths and thicknesses. Most liners are used as unsupported sheeting, but fabric reinforcement can be incorporated. PVC compounds contain 25% to 35% of one or more plasticizers to make the sheeting flexible and rubber-like. They also contain 1% to 5% of a chemical stabilizer and various amounts of other additives, including colorants. The PVC compound should not contain any water soluble ingredients. There is a wide choice of plasticizers that can be used in PVC sheeting,

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depending upon the application and service conditions under which the PVC compound will be used.

PVC membranes are the most widely used of all polymeric membranes for lining waste impoundments. They show good chemical resistance to many inorganic chemicals (Chan et al, 1978, p. 19). However, although the PVC polymer is inherently resistant to the effects of oils, plasticized PVC sheetings are attacked by many organic chemicals, e.g., hydrocarbons, solvents, and oils. Special compounds of PVC designated as Oil-Resistant PVC (PVC-OR), are available that possess high resistance to oil attack. These "oil-resistant" grades of sheeting are compounded with specialty plasticizers. Polymers such as nitrile rubber, CPE, and ethylene vinyl acetate interpolymer (EVA) may be used to replace the extractable liquid plasticizers, and thus make a PVC material more resistant to many waste liquids.

In burial tests and in some liner applications, PVC sheetings have become stiff and even brittle, presumably due to loss of plasticizer. Some plasticizers can be degraded by microorganisms or be extracted, to a limited extent, by water. On exposure to weather with its wind, sunlight, and heat, PVC liner materials can deteriorate badly due to loss of plasticizer and to polymer degradation. Plasticized PVC films are relatively resistant to puncture, and relatively easy to seam.

The specific PVC sheeting that was used as a primary liner in this study was a black plasticized PVC membrane of 20 mil thickness. An adhesive cement, supplied by the manufacturer, was used in accordance with his instructions to prepare the seam in the primary specimen.

Specimens of the same liner were also buried in the simulators, immersed in the leachate tanks and fabricated into pouches, filled with leachate and a 5% salt solution. In view of the large usage of PVC liners and the number of suppliers of this type of liner, additional PVC liner materials were included in the tests. Four additional PVC samples were buried. Seven additional PVC sheetings were subjected to leachate immersion and four to the pouch test with both leachate and 5% salt solution. One of the PVC sheetings contained pitch as the plasticizer.

ADMIX LINERS

The admix or formed-in-place liner systems include hard surface linings. They are made by:

1. Importing an admixed material, such as asphalt concrete, and placing it in thicknesses of two inches or more.

2. Mixing portland cement or asphalt with the in-place soil (or sometimes with imported soil) to form a hard surface four to six inches thick.

The four types of admix liners selected for study were asphalt concrete, hydraulic asphalt concrete, soil cement, and soil asphalt. Physical test data and composition information on the admix liner specimens which were mounted as barriers in the simulated landfills are presented in Appendix B-1.

Asphalt Concrete

Conventional paving asphalt concrete, hot-mixed and hot-laid, is readily available. Numerous contractors are experienced in its placement and have the necessary equipment. Asphalt concrete presents a hard surface resistant to traffic and impact forces. It is resistant to acids and to aging, especially in the absence of light and air. Paving asphalt concrete is designed to have a voids content of about five percent, necessary for the mechanical stability required for pavements. It has relatively low permeability to water, but often is subjected to a treatment to seal the surface. No treatment was applied to the asphalt concrete tested in this project.

The paving asphalt concrete was hot mixed and contained 7% asphalt (60-70 penetration grade). The aggregate was Watsonville granite proportioned to meet 0.25 inch maximum gradation for dense-graded asphalt. The specimens were disks 21 inches in diameter and 2.2 inches in thickness. They were compacted hot into forms outside the bases and sealed into the simulator bases with epoxy adhesive (Haxo and White, 1974; Haxo and White, 1976).

Hydraulic Asphalt Concrete

Hydraulic asphalt concrete (HAC) is also hot-mixed and hot-laid and is specially designed to have low permeability, which is achieved by controlling the gradation of the aggregate and the asphalt content to obtain a virtually voidless structure after compaction. Because it contains few voids, HAC is more susceptible to displacement and rutting under traffic than conventional asphalt concrete and, therefore, is not suitable for highway pavement. Its other properties are similar to asphalt concrete. Hydraulic asphalt concrete is mixed, laid, and compacted with the same equipment used for conventional asphalt concrete, but is more difficult to handle because of its low stability. Its cost is higher because of the extra work necessary in handling, the more stringent gradation requirements and the higher asphalt content.

The hydraulic asphalt concrete specimens prepared as primary specimens were disks 21 inches in diameter and 2.4 inches in thickness. The concrete was hot mixed and compacted in forms outside the bases. The specimens were sealed into the bases of the simulators with an epoxy resin (Haxo and White, 1974; Haxo and White, 1976). The concrete contained asphalt of 60-70 penetration grade. The aggregate was Watsonville granite proportioned to meet 0.25 inch maximum gradation for dense-graded asphalt concrete. The original voids ratio of the concrete was 2.9 percent.

Soil Cement

Soil cement is made by mixing the in-place soil with portland cement and water, and compacting the mixture. As the portland cement hydrates, the mixture becomes a hard, low-strength portland cement concrete. Soil cement is sometimes used as a surface for pavements with low-traffic volume, and is extensively used for the lower layers of pavements, where it is called "cement-treated base". Strong soil cement can be constructed with many types of soil, but permeability varies with the nature of the soil; the more granular the soil, the higher the permeability. With fine-grained soils, soil cements can be made having permeability coefficients of approximately 10^{-6} cm/sec. In practice, sealants are often applied to the surface of the soil cement to increase the waterproofness of the liner. Aging characteristics of soil cement are good, especially under conditions where wet-dry and freeze-thaw cycling are minimal. Some degradation of the cement can be expected in an acid environment. The principal difficulty with large soil cement surfaces is shrinkage, cracking, and leakage of impounded fluids.

Soil from the Radum quarry near Pleasanton, California, which had been proposed as the site of a future landfill, was used with Type 5 (sulfate resistant) portland cement for preparing the soil cement. Since the fines content of the Radum soil was lower than optimum for soil cement, a few percent of nonswelling clay (kaolin) was added. The soil cement specimens were compacted directly in the bases and sealed with a ring of epoxy resin. These specimens were 4.5 inches in thickness and were made of 95 parts of soil, 5 parts of kaolinite clay, 10 parts of portland cement and 8.5 parts of water which were thoroughly mixed before compaction (Haxo and White, 1974; Haxo and White, 1976).

Soil Asphalt

Mixed-in-place soil asphalt surfaces can be made by mixing a liquid asphalt with the in-place soil or with imported aggregate. It is widely used for low-cost pavements for low volume traffic. Permeability characteristics can be controlled by the amount and type of asphalt added. Soil asphalt is more flexible and resistant to cracking than asphalt concrete or soil cement. Liquid asphalt grade SC-800 was used to prepare the barrier specimens because it is essentially nonvolatile; MC-type liquid asphalts would be expected to leave voids when the kerosene diluent evaporated.

Laboratory specimens prepared using soil from three different locations showed that impermeable soil asphalt could be made from any of the three. Soil from the Radum quarry was selected because the location may become a landfill site. The soil asphalt specimens were four inches thick and were compacted directly in the bases. The soil asphalt consisted of 100 parts soil mixed with 7.0 parts of liquid asphalt, Grade SC-800 (Haxo and White 1974; Haxo and White, 1976). A ring seal of epoxy resin was placed on the top of the compacted liner to prevent possible bypassing of the liner by the leachate at the edge of the specimen.

SPRAYED-ON ASPHALTIC MEMBRANES

Hot-sprayed canal lining asphalt (catalytically blown asphalt) and a cold-applied asphalt emulsion sprayed on fabric were the two asphaltic membranes tested.

Catalytically-Blown Asphalt

Buried asphalt membranes have been used extensively as linings for canals and reservoirs and to seal off layers of expansive soils under pavements. This type of asphalt is made by air-blowing an asphalt in the presence of a catalyst (phosphorous pentoxide or ferric chloride), to produce an asphalt which has a high softening point, yet remains flexible at normal ambient temperatures. Membranes are applied to compacted, smooth soil surfaces by spraying the hot (200 to 220°C) asphalt in two successive applications to ensure a continuous film free of pinholes and holidays. Recommmended application rates are 4.5 to 6.8 kg/sq m (1 to 1.4 gal/sq yd) to form a film 5 to 8 mm thick (3/16 to 5/16 in.). When cooled, the membrane is flexible and tough, with low permeability to water. It is resistant to acids, but not to oily materials. Aging resistance is good when protected from light. It is usually covered with a protective layer of soil to prevent damage by traffic and deterioration by light.

The catalytically-blown asphalt membrane was cast in place at 425°F on a sand bed covering the aggregate in the base of the simulator. It was a catalytically blown canal lining asphalt and was approximately 0.30 inch in thickness (Haxo and White, 1974; Haxo and White, 1976). A ring of epoxy resin was formed around the top edge of the liner to seal the specimen in the simulator base.

Emulsified Asphalt on a Nonwoven Fabric

Emulsions of asphalt in water can be applied at temperatures above freezing. They form continuous films of asphalt after breaking of the emulsion and evaporation of the water. The films are less tough and have a lower softening point than films of hot-applied catalytically blown asphalt. Toughness and dimensional stability can be achieved by spraying asphalt emulsion onto a supporting fabric. Fabrics of woven or nonwoven glass fiber, and nonwoven synthetic fibers have been used with various anionic and cationic asphalt emulsions to form linings for ponds and canals and as reinforcing patches under asphalt concrete overlays to prevent "reflection" of cracks in the old pavement beneath. Seams in the supporting fabric are often sewn with portable sewing machines after the fabric is placed.

The liner specimen of emulsified asphalt on nonwoven fabric was an asbestos filled anionic asphaltic emulsion on a nonwoven polypropylene fabric. This membrane was prepared by the supplier in sheet form with a seam. Disk specimens, 22 inches in diameter, were cut from the sheets, mounted in the bases, and sealed with epoxy resin. These liner specimens were 0.30 inch thick.

SELECTION OF MATERIALS FOR THE PRIMARY EXPOSURE TESTS IN THE LANDFILL SIMULATORS

The specific materials that were selected for exposure as primary test specimens and mounted in the bases of the simulators are listed in Table 4.

SELECTION OF SECONDARY TEST SPECIMENS

Secondary test specimens, consisting of 42 coiled strips of polymeric membrane liner materials, were buried in the sand layers above the thin primary liners. During the operation of the simulators, these specimens were expected to be completely immersed in leachate. They were added to the study to increase the range of materials in the program, to assess the impact of

TABLE 4. LINER MATERIALS SELECTED AS PRIMARY TEST SPECIMENS FOR MSW LEACHATE EXPOSURE TESTS

Material	Thickness
Polymeric membrane liners:	
Butyl rubber (IIR)	63 mils
Chlorinated polyethylene (CPE)	32 mils
Chlorosulfonated polyethylene (CSPE) nylon scrim reinforced	34 mils
Ethylene propylene rubber (EPDM)	51 mils
Low density polyethylene (LDPE)	10 mils
Polyvinyl chloride (PVC)	20 mils
Admixes:	
Hydraulic asphalt concrete	2.4 in.
Paving asphalt concrete	2.2 in.
Soil asphalt	4.0 in.
Soil cement	4.5 in.
Sprayed-in-place membranes:	
Catalytically blown asphalt	0.3 in.
Asphalt emulsion on nonwoven fabric	0.3 in.

exposure to leachate to both sides of the liner membranes, and to obtain information needed to develop new liner evaluation test methods. Almost all of the secondary test specimens were fabricated with a splice. Thus, different seaming systems could be tested in the project. The buried specimens consisted of the following:

- Samples of the polymeric sheetings which were mounted in the simulators and which had a splice made by the same seaming system as the primary test specimen.

- Samples of the polymeric sheetings which were mounted in the simulators and which had a splice made with a different seaming system than the primary test specimen.

- Samples of additional sheetings based on the same six polymers as the primary test specimens. These sheetings differed from the primary test specimens in that they were either of a different thickness, with or without fabric reinforcement, or produced by a different manufacturer.

- Samples of additional sheetings based on polymers which appeared to have potential for use as liners, i.e. neoprene, polybutylene, and polypropylene.

- A series of five gasket sheetings of different polymer compositions.

- Molded slabs of two thermoplastic elastomers based on polyolefins.

- A piece of asphalt roofing paper.

The five gasket materials had been candidates for sealing the column to the base in the simulators and had been recommended for service in moist environments. Because of the unevenness in the flanges of the columns, the neoprene sponge was selected to seal the simulators. The two thermoplastic elastomers appeared to be potential raw materials for liner sheetings. Small slabs were molded at our laboratory. The roofing asphalt was included because of its general availability and its use in waterproofing applications. Preliminary testing showed it to have a low elongation and we felt that it would not be suitable for a lining material, but since it was an asphaltic material containing fillers, we thought that it should at least be subjected to a burial test.

The different types of polymeric sheetings selected for testing in the secondary exposure are listed in Table 5. Also presented are the number of different sheetings tested, the number of different bonding systems tested in combination with sheetings of a specific polymer type, and the total number of specimens of a specific polymer type tested per exposure period. The splices in the exposure specimens were made either by the manufacturer or in the laboratory. Most of the specimens made in the laboratory were seamed in accordance with the manufacturers' directions. In some cases a bonding system recommended by one manufacturer was used with a sheeting made by another manufacturer. All specimens were exposed in duplicate to allow for two exposure periods.

After 43 months of exposure, two of the landfill simulators were lifted off their bases so that the primary liners could be inspected. At that time, the secondary exposure specimens in those cells were removed for testing and replaced by ten other specimens. The types of sheetings placed in exposure at that time are listed in Table 6. These included two new types of sheetings that were introduced to the market after 1973. The others were from samples received after the simulators were put into operation. Some of the specimens contained splices. With one exception, all the splices were made using a thermal-based technique.

IMMERSION SPECIMENS

The similarity of the results of testing the primary and secondary test specimens indicated that immersion testing was a feasible means of assessing the effects of MSW leachate on polymeric lining materials. Twenty-eight specimens of eleven different polymers were chosen for immersion testing. The chosen specimens represented a broad cross section of the polymeric membrane liner materials available at that time. In addition, an effort was made to test several compositions of selected polymeric compounds. A list of the types of polymeric compounds tested is presented in Table 7. A more detailed discussion of immersion testing is presented in Section 9.

TABLE 5. MATERIALS SELECTED FOR SECONDARY EXPOSURE TEST AT BEGINNING OF TEST

Type of polymer	Number of different sheetings tested	Number of different bonding systems tested	Number of specimens tested per exposure period
Asphalt fiberglass roofing	1	0	1
Butyl rubber	3	1	3
Chlorinated polyethylene	3	4	12
Chlorosulfonated polyethylene	4	4	6
Ethylene propylene rubber	4	2	4
Natural rubber	1	0	1
Neoprene	3	1	3
Polybutylene	1	1	1
Polypropylene	1	0	1
Polyvinyl chloride	5	2	6
Styrene butadiene rubber	1	0	1
Thermoplastic rubber	2	0	2
Urethane rubber	1	0	1
Totals	30		42

TABLE 6. MATERIALS PLACED IN SECONDARY EXPOSURE AFTER 43 MONTHS OF OPERATION OF LANDFILL SIMULATORS

Type of polymer	Number of sheetings	Number of bonding systems	Number of specimens
Chlorinated polyethylene	1	1[a]	1
Elasticized polyolefin	1	1[b]	1
Ethylene propylene rubber	1	0	1
Neoprene	1	0	1
Polybutylene	1	1[a]	1
High-density polyethylene	1	1[b]	1
Polyvinyl chloride	4	2[c]	4
Total	10		10

[a] Matrecon heat seam.

[b] Seam made by manufacturer.

[c] One seam made by Matrecon using a heat technique; second seam made by manufacturer with either a solvent or a bodied solvent.

Table 7. TYPES OF POLYMERIC COMPOUNDS SELECTED FOR IMMERSION TESTING

Butyl rubber (IIR)
Chlorinated polyethylene (CPE)
Chlorosulfonated polyethylene (CSPE)
Elasticized polyolefin (ELPO)
Ethylene propylene rubber (EPDM)
Neoprene (CR)
Polybutylene (PB)
Polyester elastomer
Polyethylene - low density (LDPE)
Polyvinyl chloride (PVC)
Polyvinyl chloride and pitch

SECTION 7

CHARACTERIZATION OF MUNICIPAL SOLID WASTE AND FILLING OF SIMULATORS

In order to evaluate the effects of leachate upon the different liner materials being tested and to be able to compare the results, the municipal solid waste loaded into each of the simulators should have the same general composition so that the leachate generated in each of the simulators is essentially of the same quality. In addition, if the project is to be used to study the effects of leachate from a typical MSW landfill, the waste used should be representative of municipal solid waste in the United States. In this section, the municipal solid waste used in the project and the procedure used for loading the simulators are described.

CHARACTERISTICS OF MUNICIPAL SOLID WASTE USED IN THE PROJECT

It was originally planned to load the simulators with a "manufactured" refuse made by blending components typical of municipal solid wastes according to a "recipe". This "manufactured" refuse was to have a minimum of 15 percent food wastes. The components would have been collected separately, e.g. paper, boxes, garden waste, food waste, etc. These materials would have been blended and ground at the Richmond Field Station, University of California, Berkeley. All materials except the putrescibles were collected.

The project officers later requested that ground municipal refuse, collected from a residential area, be used in the simulators. At the time we were to load the simulators, the grinder at the Richmond Field Station was not operable. Arrangements were then made with Combustion Power Company and the Palo Alto Sanitation Company to supply municipal waste from Palo Alto, shredded in an Eidal Mini-Mill Grinder (Model 100) at Combustion Power Company.

Approximately 12 tons of refuse, collected in the residential area of Palo Alto, California, was supplied to Combustion Power Company, who ground the material without classification over a period of a week in the Mini-Mill. The shredded refuse was delivered to the Richmond Field Station in three loads for systematic loading into the 24 simulators.

It was the consensus of Combustion Power and the Palo Alto Sanitation Company personnel who saw the refuse before it was ground that it was typical of the refuse which is normally collected in the Palo Alto area and received at the Combustion Power laboratory, except that it appeared dry.

During the loading of the simulators, a composite grab sample was accumulated by collecting one scoopful of refuse from each individual load added to the 24 cells. The entire composite sample of 32.8 kg (72.2 lb.) was separated into four size fractions by screening through a Sweco separator fitted with 25 mm (1 inch), 13 mm (0.5 inch) and 6 mm (0.25 inch) sieves. The entire 4.2 kg (9.3 lb) 6-13 mm fraction, and 4.2 kg aliquots of the plus 25 mm and 13-25 mm fractions, were classified by hand sorting.

The fraction of less than 6 mm was not hand sorted, but an aliquot of it was dried and ashed, and another aliquot was dried and separated by flotation with trichlorethane (density, 1.34 g/cm^3) and carbon tetrachloride (density, 1.6 g/cm^3) into fractions with density <1.34, 1.34 to 1.6 and >1.6, and a fraction soluble in trichlorethane, i.e., oils and fats. Moisture content of the less than 6 mm fraction was 17%, ash content 49%, and organic content 34%. Examination showed that the <1.34 density fraction was food waste and garden trash, while the >1.6 density fraction was mostly glass and soil. The 1.34-1.6 density fraction appeared to be mostly paper fiber (cellulose density = 1.4).

Table 8 shows the composition of the composite refuse sample. The content of identifiable food waste was low. It is assumed that the refuse was collected from a neighborhood where most food wastes are flushed into the sewers through sink disposal units. The actual content of putrescible organic material was somewhat higher than shown, as some pieces of paper and plastic in the larger size fractions were obviously saturated with fats, blood, etc.

PROCESSING AND LOADING OF MUNICIPAL SOLID WASTE INTO SIMULATORS

The residential municipal solid waste delivered to Combustion Power Company was highly nonhomogenous. To obtain the necessary homogeneity for the exposure study, good blending, as well as uniform loading and compacting of the solid waste in the simulators, was required. Some blending of the contents of the packer truck occurred on the floor of Combustion Power Company and in the feeding and grinding of the refuse in the Eidal shredder. However, the grinding and delivery of the refuse took place in three different loads and each had a different overall appearance. To insure that the same composition and amount of refuse was placed in each of the generators, the following plan for loading the refuse into the generators was established:

1. Initially the refuse was weighed into 30 pound aliquots and dumped into simulators one after another in rotating order.

2. After each load, the refuse was compacted, using the two hand compactors specifically designed for this purpose (Figure 8).

3. Care was taken during the first few lifts of refuse to avoid heavy compaction because of the possible damage to the liners and disturbance of the test specimens which had been buried in the sand above the barriers. It was found, however, that the refuse was difficult to compact because of its low moisture content. Consequently, one gallon of water was added to each load after weighing it before it was introduced into the simulators. In addition, the

TABLE 8. CHARACTERIZATION OF COMPOSITE SAMPLE OF REFUSE

	Fraction size				
	>25 mm (>1 in.)	13-25 mm (0.5-1 in.)	6-13 mm (0.25-0.5 in.)	<6 mm (<0.25 in.)	Total
Classification, % of composite					
Water	3.2	4.3	0.6	4.0	12.1
Paper	18.8	21.4	6.5	6.9	53.7
Cloth	0.3	0.4	0.1	...	0.8
Plastic and rubber	2.6	2.0	0.3	...	4.9
Wood, garden, and food waste	0.6	2.4	1.3	0.8	5.1
Oils and fats	...	...	...	0.9	0.9
Metal	1.5	5.5	0.5	...	7.5
Glass, rock and soil	...	0.8	3.6	10.5	15.0
Total, % of composite	27.0	36.8	12.9	23.2	100

weight of the individual loads per lift was reduced, after the fifth rotation, to 20 pounds.

Approximately 950 pounds of refuse, having a water content of 12-15%, was added to each of the simulators in 45-47 loads or lifts (Table 9). This amount is equivalent to 1150 pounds of refuse per simulator or about 1240 pounds per cubic yard for the refuse of 30% water content.

Screened topsoil was added and compacted to a depth of approximately 1.75 feet on top of the refuse, and three inches of 3/4-inch drain rock was added on top of the soil. In most of the simulators, it was necessary to add the rock after the addition of water had been started to bring the refuse to field capacity. During this time the refuse consolidated and settled, allowing space for the rock to be placed on top of the soil. The top of the soil was given a saucer shape so that when the water was added it would pool in the center of the columns and not drain to the periphery and channel down the edges near the walls. If that were the case, the resultant leachate would not have been up to full strength.

BRINGING THE REFUSE TO FIELD CAPACITY

The original plan was to bring the refuse in the simulators to field moisture capacity over a period of 30 days. Calculations were made, based

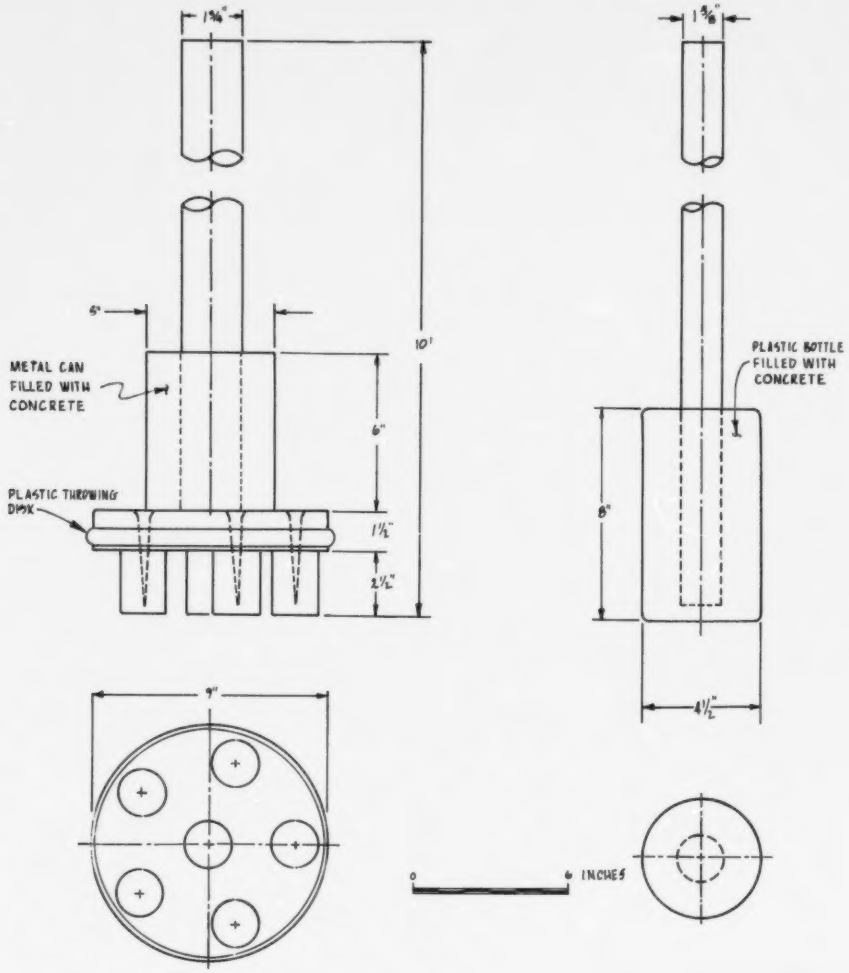
1¾"
1⅜"
5"
10'
METAL CAN FILLED WITH CONCRETE
6"
PLASTIC THROWING DISK
1½"
2½"
PLASTIC BOTTLE FILLED WITH CONCRETE
8"
4½"
9"
0
6 INCHES

Figure 8. Hand compactors used to compact the refuse in the simulators. The compactor on the right was used to compact on the periphery and the compactor on the left was used to compact in the center of the simulators.

upon the moisture analysis of the refuse and upon an estimate of the amount of water added to aid in compaction. The results were that it would take approximately one gallon of water per day on a five day per week basis to reach this goal. Several of the simulators appeared to produce leachate early; however, they did not continue producing, and the other simulators did not begin to produce leachate on schedule. Therefore, we decided to add two gallons of water per day. The conclusion was that the formation of a water "plug" caused generation of leachate in some of the simulators before they reached field capacity.

All of the simulators reached field capacity and produced leachate on a continual basis within seven weeks. The number of days each took to produce first leachate, the amount of water added, and total leachate produced as of the forty-ninth day when all simulators were saturated and considered to be at "field capacity" are shown in Table 9. The forty-ninth day is taken as the starting point for the exposures.

TABLE 9. LOADING OF SIMULATORS WITH REFUSE AND BRINGING REFUSE TO FIELD CAPACITY

Simulator number	Number of loads[a]	Amount of refuse[b], lb	Amount of water added during compaction[c]	Days to produce first leachate	Amount of water added in 48 days, gal[d]	Amount of leachate as of 49 days, gal[e]
1	45	950	444	13	26.5	3.8
2	45	950	444	27	33.5	4.6
3	45	950	444	37	38.5	5.3
4	45	950	444	24	33.5	5.2
5	45	950	444	27	35.5	3.4
6	45	950	444	40	38.5	3.8
7	45	950	444	37	36.5	4.6
8	45	950	444	45	40.5	1.9
9	45	950	444	45	40.5	0.9
10	45	950	444	45	40.5	1.8
11	45	950	444	17	30.0	5.1
12	45	950	444	45	40.5	2.6
13	45	950	444	37	34.5	4.6
14	45	950	444	35	36.5	5.6
15	45	950	444	35	36.5	4.5
16	45	950	444	41	40.5	2.2
17	45	950	444	27	33.5	2.6
18	45	950	444	45	40.5	2.2
19	46	970	454	46	40.5	1.4
20	45	950	444	46	40.5	1.7
21	45	950	444	33	40.5	1.9
22	45	950	444	42	40.5	1.5
23	47	990	464	45	40.5	1.6
24	47	990	464	41	38.5	3.4

[a] Number of loads added; the first five loads were 30 lbs. each, the next 30-32 were approximately 20 lbs. each.

[b] Amount of refuse added, pounds; estimated water content of the refuse was 12-15%.

[c] Amount of water added during compaction, pounds.

[d] Water added, as of 11/21/74, gallons; first water added October 4 to bring the refuse to field capacity. Two gallons of water equals 1 inch depth in the column.

[e] Leachate produced as of November 22, 1974, when all simulators were saturated and considered to be at field capacity, gallons.

SECTION 8

EXPOSURE TESTING OF PRIMARY AND BURIED LINER SPECIMENS IN MSW LANDFILL SIMULATORS

The primary thrust of this study was to determine the effects upon various liner materials of exposure to MSW leachate in an environment that closely simulated conditions in an actual full-scale landfill containing municipal solid waste. In this section we report on the exposure of the various liner materials that were placed as primary liners in the simulators and those buried in the bases of the simulators. Also reported are data on the performance of the simulators, the quality of the leachate, and the condition of the refuse. The objective of the latter discussion is to describe the actual environment in which the liner materials were exposed.

The primary and buried liner specimens were placed in exposure in November 1974. After one year, in November 1975, 12 of the 24 simulators were dismantled and the liners were recovered and tested. At 43 months, two simulators were opened, the buried specimens removed and tested, and the primary liners inspected, sampled, and repaired. At 56 months, the 12 simulators in the second set were dismantled and the exposed primary and buried samples were removed and tested.

Seaming of the polymeric membranes and results of the exposure testing of the seams in the simulators are discussed in Section 11. Results of immersion exposure of polymeric membranes in leachate are presented in Section 9.

OPERATION OF SIMULATORS AND LEACHATE GENERATION

Monitoring and Operation of the Simulators

Once the simulators were producing leachate and the exposure of the liner materials had begun, the following monitoring tasks were performed to insure the proper functioning of the simulators and to obtain data on the conditions under which the liners were exposed:

1. Two gallons of tap water were added biweekly to each of the simulators. This is equal to one inch of water per two weeks or 26 inches per year.

2. The leachate was collected from above the respective liners, also on a biweekly basis. Initially, the leachate was allowed to remain in the simulators and then drained by opening a valve and collecting it in a bag. This collection was generally slow. Later, the collection was changed to allow drainage from the simulators to be continuous

and the level of the leachate above the liners was kept constant by use of a "U" tube.

3. The cavity below the liners was checked biweekly for the presence of leachate and when leachate was observed, a bag was placed to collect it continuously.

4. The ambient temperature and the temperature within four of the simulators was recorded biweekly until the thermocouples failed. The leachate was analyzed on a four-week basis for the following:

   Chemical oxygen demand (COD)
   Total solids
   Volatile solids
   Total volatile acids as acetic acid.
   Individual volatile acid (first year only).

   Note: All analyses of the leachate were made by personnel of the Sanitary Engineering Research Laboratory of the University of California, Berkeley.

5. The height of the contents within the columns was measured intermittently during the course of the operation of the simulators.

The 24 simulated sanitary landfills in which the liner material specimens were exposed were erected in an unheated wooden frame building at the Richmond Field Station of the University of California, Berkeley. The windows of the building remained open. This station is on the eastern shore of the San Francisco Bay in Richmond, California. The temperature in this building is relatively cool and uniform, ranging from 8 to 27°C (46-81°F), but usually in the 10-20°C range, a temperature likely to be encountered at the base of landfills.

For the first few days of the operation of the simulators, the temperature of the refuse rose a few degrees above ambient but later it dropped and was essentially the same as ambient temperature. The observations were usually made in the morning, at which time the ambient and the refuse temperatures were equal. During the course of the day, the ambient temperatures would rise and there would be a small rise in the temperature of the refuse. Throughout the operation of the simulator, the temperature of the refuse was usually in the 10-20°C range, and occasionally on warm days the temperature rose to 27°C.

Leachate Quality

The simulators were brought to field capacity over a period of a month by the addition of tap water. The high quality of this water is shown in Table 10. Water equivalent to two inches of rainfall per month was added biweekly to produce the leachate which was used throughout these studies. Overall, the production of leachate by each simulator equaled the amount of water that was added, except for minor deviations resulting from seepage or leakage below the liner and individual collection variations. The average compositon of the leachate at the end of the first year, when the first set of simulators was disassembled and the liner specimens were recovered and tested, is shown in Table 11. An analysis of all the leachates produced in the simulators after 11 months of operation is presented in Appendix C-1 to show the range of concentrations.

TABLE 10. CHARACTERISTICS OF WATER ADDED TO SIMULATORS

Constituent or property	Concentration, mg/L except pH and conductivity
Cations	
Calcium, Ca	6.0
Magnesium, Mg	0.6
Sodium, Na	1.3
Potassium, K	0.5
Anions	
Chloride, Cl	2.0
Carbonate, CO_3	1.1
Sulfate, SO_4	0.9
Nitrate, NO_3	0.05
Bicarbonate, HCO_3	18.0
Phosphate, PO_4	0.013
Other	
Hardness, total as $CaCO_3$	17.5
Alkalinity, as $CaCO_3$	17
Total dissolved solids	33
pH	9.1
Electrical conductivity, µmhos/cm	45

Source: East Bay Municipal Utility District, Oakland, California, December 1975.

The strength of the leachate, as measured by total solids, nonvolatile solids, and total volatile acids decreased with time as is shown in Figures 9 and 10. The compositions of the individual leachates from the 12 simulators, which were retained in operation after the first group of liners were recovered and tested in November 1975, were initially quite uniform. However, in later months the average strength of the leachates decreased significantly and differences in compositions developed. Beginning in November 1978, nutrient (urea) was added with the water to all but one of the simulators to increase the organic content of the leachate, particularly of the volatile acids; however, the concentration of the acids continued their downward trend (Figure 9). Figures 11 and 12 show the pH and chemical oxygen demand (COD) characteristics of the leachate over the duration of the operation of the simulators. The pH tended to go through a minimum of about 5.0 which lasted from about six months to 24 months, after which it gradually rose to over 7.0. The COD maintained high values in the range of 40-50,000 mg/L after which it dropped to less than 10,000 mg/L in about 15 months. An analysis of all the

TABLE 11. ANALYSIS OF LEACHATE[a]

Test	Value
Total solids, %	3.3
Volatile solids, %	2.0
Nonvolatile solids, %	1.3
Chemical oxygen demand (COD), g/L	45.9
pH	5.05
Total volatile acids (TVA), g/L	24.33
Organic acids, g/L	
Acetic	11.25
Propionic	2.87
Isobutyric	0.81
Butyric	6.93

[a] Based on an analysis of leachate collected from Simulators 13-24 on November 10, 1975, just before the first set of liner specimens were recovered and tested.

leachates produced by the landfill simulators after 54 months of operation is presented in Appendix C-2.

Collection of leachate below the primary liner was designed to be used as a measure of the permeability of the liners. Leachate was collected below the liners during the first year in three of the 24 simulators. They were all in the first set of 12 that were dismantled at the end of one year (Table 12). When the bases were opened to recover the liner specimens, it was obvious that the epoxy seal around the hydraulic concrete specimen had crumbled and failed. Two other seals had softened or crumbled, but had not failed. During the subsequent time until the final dismantling of the simulators, leachate was collected below the liner in five of the remaining 12 simulators. On examining the seals after the bases were cleaned, three were found to have disintegrated and failed. The other two seals for the soil asphalt and soil cement were in good condition; therefore, the leakage that had taken place was through the liners. The leakage was confirmed by the pressure leak test performed at the time the simulators were dismantled and by permeability measurements of the cores taken from the exposed liner specimens.

Dismantling of Simulators and Recovery of Liner Specimens after 12 Months of Exposure

Twelve of the 24 MSW landfill simulators containing the liner test specimens were dismantled in November 1975 and the specimens were recovered for laboratory testing. The recovery was performed 52 weeks after the refuse in the columns had been brought to field capacity and leachate began ponding on the primary specimens mounted in the bases.

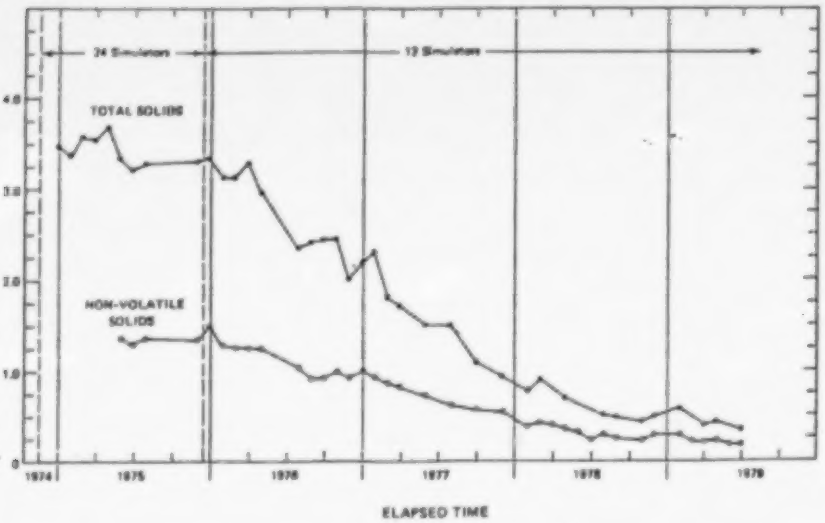

Figure 9. Average solids contents of the leachate produced in the simulators, November 1974 - July 1979. The data for November 1974 - November 1975 are the averages for the leachate from 24 simulators. Twelve simulators were disassembled in November 1975 and, consequently, the data for December 1975 - July 1979 are the averages for the leachates from the 12 remaining simulators.

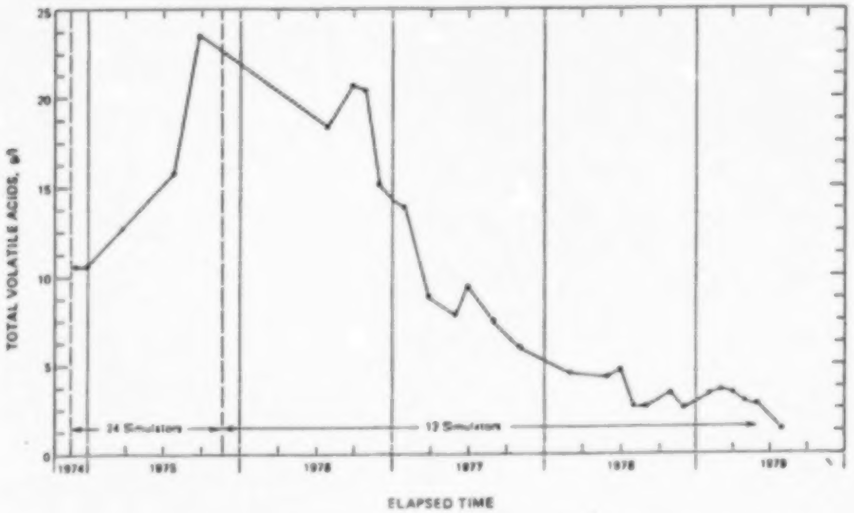

Figure 10. Average total volatile acids content (TVA), as acetic acid, of the leachate produced in the simulators, November 1974 - July 1979. The data for November 1974 - November 1975 are the averages for the leachates from 24 simulators. The data for December 1975 - July 1979 are the averages for the leachates from 12 simulators.

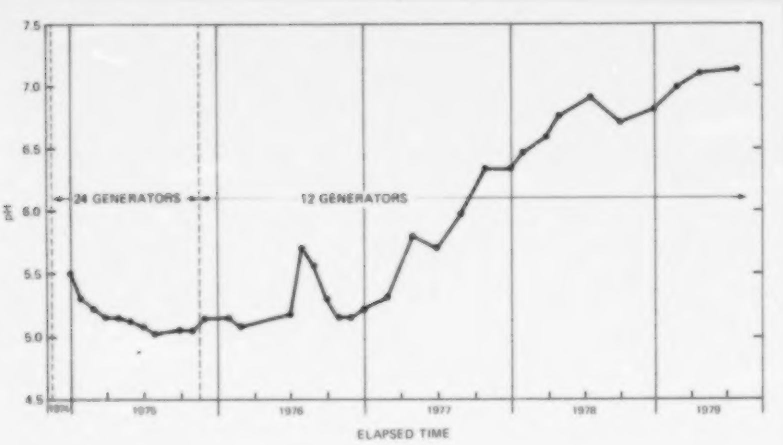

Figure 11. Average pH of the leachate produced in the simulators, November 1974 - July 1979. The data from November 1974 - November 1975 are the averages for the leachates from 24 simulators. The data from December 1975 - July 1979 are the averages for the leachates from 12 simulators.

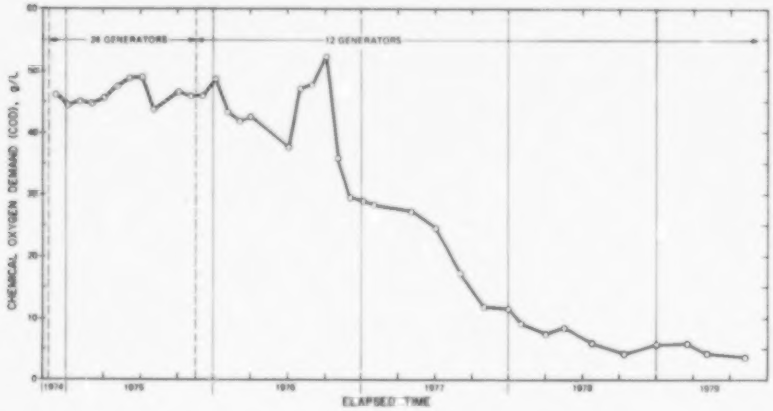

Figure 12. Chemical oxygen demand (COD) of the leachate produced in the simulators, November 1974 - July 1979. The data for November 1974 - November 1975 are the averages for the leachates from 24 simulators. The data for December 1975 - July 1979 are the averages for the leachates from 12 simulators.

TABLE 12. COLLECTION OF LEACHATE BELOW PRIMARY LINER SPECIMENS IN SIMULATORS

	Simulators dismantled at 12 months					Simulators dismantled at 56 months					
							Amount collected, kg				
Primary liner material	Simulator number	Amount collected, kg	Bubbles in pressure test[a]	Condition of epoxy seal	Permeability test	Simulator number	1-12 months	13-56 months	Bubbles in pressure test[a]	Condition of epoxy seal	Permeability test
Admixes											
Paving asphalt concrete	13	12.3	Yes	Crumbled	Yes	7	0	0	No	Crumbled	Yes
Hydraulic asphalt concrete	14	3.24	Leak in seal	Failed	Yes	8	0	0	No	Good	Yes
Soil cement	15	0	No	Good	Yes	9	0	0.23	A few	Good	Yes
Soil asphalt	16	12.1	Yes	Good	Yes	10	0	1.42	A few	Good	Yes
Asphalt membranes											
Catalytically-blown asphalt	17	0	No	Good	N/A[b]	11	0	0	No	Good	N/A
Emulsified asphalt	18	0	No	Good	N/A	12	0	0	No	Good	N/A
Polymeric membranes											
Polyethylene	19	0	No	Good	N/A	1	0	>67	-	Failed	N/A
Polyvinyl chloride	20	0	No	Good	N/A	2	0	>2	-	Failed	N/A
Butyl rubber	21	0	No	Good	N/A	3	0	>107	-	Failed	N/A
Chlorosulfonated polyethylene	22	0	No	Good	N/A	4	0	0	No	Good	N/A
Ethylene propylene rubber	23	0	No	Good	N/A	5	0	0	No	Good	N/A
Chlorinated polyethylene	24	0	No	Good	N/A	6	0	0	No	Good	N/A

[a] Test of leaks in liner or epoxy seal and their locations. After cleaning of liner surface, the base above the liner was flooded with water and the space below the liner was pressurized with air; the appearance of bubbles in the water indicated the leaks.

[b] N/A = Not applicable.

A major problem faced in dismantling and recovering the exposed liners was to perform the operations without damaging the primary liner specimens and thus be able to make an in-place test for leaks of the liner and the epoxy seal. The individual filled columns weighed approximately 3000 pounds consisting of:

	Pounds
Steel pipe	400
Refuse + water	1690
Soil cover, 1 2/3 ft.	800
Rock, 1/3 foot	150
Total	3040

To raise the columns of waste vertically, a split collar was fabricated with horizontal pins that could be bolted to the refuse filled steel pipe above its center of gravity. Using a four-ton forklift, an individual column was lifted vertically at the pins and tilted after it had cleared the base, at which time a steel cover was placed over the opening of the column to prevent refuse from falling out.

Both the columns and the bases were removed from the building without problem. The bases had been cast on butyl rubber sheeting which had been placed on the floor of the building and, thus, they could be lifted off the floor and moved away.

To prepare for dismantling, we performed the following:

1. Stopped the addition of water two weeks prior to dismantling.

2. Allowed the leachate to drain throughly from the refuse.

3. Removed the soil and rock cover from above the refuse in the columns.

4. Detached all bolts, bags, tubing, etc.

The dismantling proceeded without incident, except where the entire contents of one of the columns in the polyethylene casing slipped out of the pipe; this gave us the opportunity to examine the full depth of the refuse in the simulator.

After removing the buried specimens and the sand for each base, the liner surface was flushed with water. The liners and epoxy seals were photographed. The liner specimens and seals were tested for leaks by flooding the surface of the liner up to above the level of the epoxy seals with water, pressurizing the space below the liner, and then observing whether bubbles developed and rose through the water. The polymeric membranes were then cut out of the bases, as were the blown asphalt and emulsified asphalt membranes. Six two-inch cores (two near the center and four in the periphery) were cut with a diamond core drill from each of the admix liners except the soil asphalt. The top part of the soil asphalt had become almost a soft mud which disintegrated within the drill. No full-length, intact cores could be obtained of this material, but as the lower portion was firmer than the top, partial cores were obtained for testing.

Opening of Simulators 11 and 12 for Examination of Primary Liners and Recovery and Testing of Buried Specimens

In view of the relatively long interval of time the simulators had operated after the first set was dismantled (approximately 2.5 years) and because significant information could be obtained, it was decided to open two of the simulators approximately one year before the dismantling was scheduled. The objectives of this task were:

- To determine the condition of the two asphalt membranes under test.
- To recover the strip membrane specimens that had been exposed to leachate for 43 months.
- To cut out a sample of one liner and make a repair which would be tested by returning the simulator to operation and observing whether any leachate entered the cavity below the liner.
- To assess the feasibility of opening the landfill simulators.
- To determine the impact of disturbing the refuse on leachate quality by analyzing the output before and after the simulator had been opened.
- To expose 10 new polymeric membrane materials to leachate by burying them in the sand above the primary liners.
- To examine the refuse.

The procedure of opening the simulator, the inspection of the condition of the liners and of the refuse, and the repair of the hole cut in the liner are discussed in this subsection.

Preparation of the simulators for the opening began with analyses of the leachate produced by each of the two simulators to give a basis of comparison for determining if any changes in leachate quality would occur after returning the simulator to operation. About one week before the operation, draining of simulators 11 and 12 was begun to empty them of leachate. Approximately 19 kg of fluid was removed from each simulator.

The disassembly of the simulator began with removal of the soil and gravel cover above the refuse (Figure 2), in order to reduce the overall weight of the cell and also to lower its center of gravity. A steel collar was then bolted to the column and the cell base was unclamped. A two-ton fork lift was used to lift the column slightly to slide and clamp a thin steel plate to the column bottom, preventing any refuse from sliding out. The column was then lifted, swung out, and set down on wood blocks while the liner was inspected. The procedure was repeated for the second simulator.

A small amount of refuse was left in the concrete base after the column of refuse was removed. Inspection of this material revealed that, after 43 months of exposure to leachate in a simulated landfill, many materials were not greatly degraded, such as newsprint, paper labels, polyethylene food containers, clothing, polyvinyl chloride containers, etc. After inspection, the refuse was removed and the polymeric strip specimens were recovered from the sand layer above the primary liner. The specimens were sealed in polyethylene bags to prevent moisture loss until they could be tested. The remaining sand was removed and the asphalt liner was examined. Sand was imbedded in the liners of both simulators and asphalt had accumulated around the leachate drain pipes. The liners were found to be intact and still serviceable as barriers to leachate. A sample was cut from the emulsified asphalt liner of Simulator 12 and a repair made to resemble a sampling operation of a liner in a sanitary landfill. The sample cut out exhibited a large increase in thickness, indicating that leachate exposure caused swelling in this type of liner. The sample was placed in a polyethylene bag for later testing. A patch of nonmetallic, nonshrinking grout was poured into the hole, which was prepared by digging out the gravel beneath the liner, allowing an excess of grout to seal around the edges (Figure 13). The grout made a satisfactory seal which prevented any leachate from passing through for 13 months. Although the long-term effects of leachate exposure on this material are not known, the grout was quite firm when the liner was retrieved.

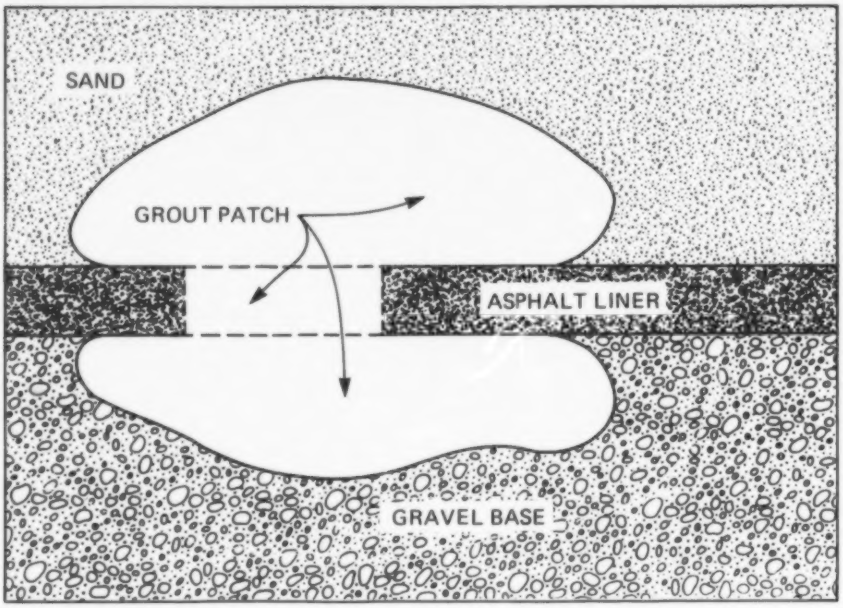

Figure 13. Grout patch made to seal hole cut in asphalt liner.

After the inspection of the two liners was completed and after the grout patch had set in Simulator 12, the sand layer was replaced and a new set of polymeric strip membranes was buried. These consisted mainly of samples which had been received since the project was started and some which had not been tested. A list of the materials is given below:

Simulator 11:		Liner number
	Elasticized polyolefin	36
	Polyvinyl chloride	67
	Polyvinyl chloride	93
	EPDM	94
	Polyethylene	99

Simulator 12:		Liner number
	Chlorinated polyethylene	38
	Neoprene	82
	Polyvinyl chloride	88
	Polyvinyl chloride	92A
	Polybutylene	98

An attempt was made to replace the refuse column upon the base of Simulator 12, but the refuse began to slide out when the steel plate was removed prior to clamping the column in place. It was not possible to force the refuse back in or seat the column on the base, so the excess refuse was removed and the holding plate was clamped back on the flange.

On the following day, holes were drilled in the wall of the pipe about two inches above the bottom of the column and two steel rods were forced through the refuse at right angles. This arrangement held back the refuse sufficiently well so that the column could be seated on the concrete base, clamped down, and sealed. This procedure was repeated on Simulator 11 and the holes in the column walls were temporarily sealed with a butyl caulking compound. A permanent seal was later made by tapping the holes and securing a bolt in the hole. The soil and gravel were replaced in the top of the column and refuse, soil, and gravel heights were measured. Water was added to bring the simulators back to field capacity, which was achieved after the addition of about 30 kg of water. A leak from one of the bolt holes in Simulator 12 caused the loss of the first batch of leachate, but judging by the leachate from Simulator 11's production, it can be estimated that about 2-3 ky of leachate were produced during the first collection, about two weeks after the resassembly. Tightening the bolt was sufficient to eliminate the leakage and both simulators produced leachate at normal rates.

Results of the testing of the samples recovered from the simulators are reported later in this section.

Dismantling of Simulators and Recovery of Liner Specimens at 56 Months

The 12 simulators of the second set were dismantled in August 1979 after 56 months of operation. Both the primary and buried specimens were recovered and tested. The procedure followed in the dismantling was essentially the same as that used in dismantling the simulators after 12 months of exposure. At the time of the dismantling of the second set of simulators, the contact adhesive at the bottom of the columns had disintegrated and the refuse was more dense and more difficult to prevent from falling out of the columns when they were lifted off the bases.

In several of the bases of the simulators, it was apparent that the epoxy seals had swelled and deteriorated considerably more than at the end of 12 months. Several seals had deteriorated to the point where leakage and bypassing of the liner had taken place. In these cases, neither the permeability of the liner nor the presence of holes could be assessed. However, most of the epoxy seals withstood the leachate. The materials from which the seals were made was a two-component fast-curing epoxy resin, which is sensitive to water and to error in mix ratios. We feel that those seals that failed were either inadequately mixed or had incorrect mix ratios. Epoxy resins that are more chemically resistant are now available and would be more suitable for sealing the liners into the bases.

In several of the bases we observed cementitous hardening of the sand which required effort to break up; this cementitious build-up also developed around the drain pipes. Although there was leachate flow in all but one of the simulators, it appeared that, in time, this build-up could have completely plugged the drains and stopped the leachate from flowing out of the simulators. When treated with dilute hydrochloric acid, this hardened sand bubbled indicating that carbonates had built up. Such build-up could cause problems in drainage systems in large-scale landfills where leachate and carbon dioxide are generated.

Before removing or cutting the exposed liner specimens, the bases were flooded and the space below the liners was slightly pressurized to determine whether there were any leaks in the liners. This procedure also determined whether there were any leaks in the epoxy seal around a liner.

Observations and the results of testing the liner specimens are reported below in this section. The results of the adhesion and seam strength testing are reported in Section 11.

Consolidation and Condition of Refuse During Operation of Simulators

The heights of the contents of the simulators were monitored regularly during the course of the project. A gauge had been placed on the refuse at the time the simulators were loaded as shown in Figure 2. The averages of the consolidation are plotted against time in Figure 14. During the first year, 24 simulators were included in the average. After the first set was dismantled, the average was based on 12 and later, during the last year, five simulators were included in the averages.

During the 244 weeks that the simulators were in operation, the refuse consolidated relatively linearly (about 20%). After 220 weeks, the consolidation appears to have been leveling off but even at 244 weeks, when the simulators were dismantled, some consolidation was continuing.

When the first set of simulators was dismantled after 12 months operation, the refuse was inspected and photographed. The appearance of the refuse showed that it had deteriorated very little during the course of the year. Newsprint could be read and colors were retained in both paper and pieces of fabric. Organic material, leaves, twigs, etc. also showed little damage. Pieces of plastic and metal (aluminum, tin cans, pennies, etc.) were

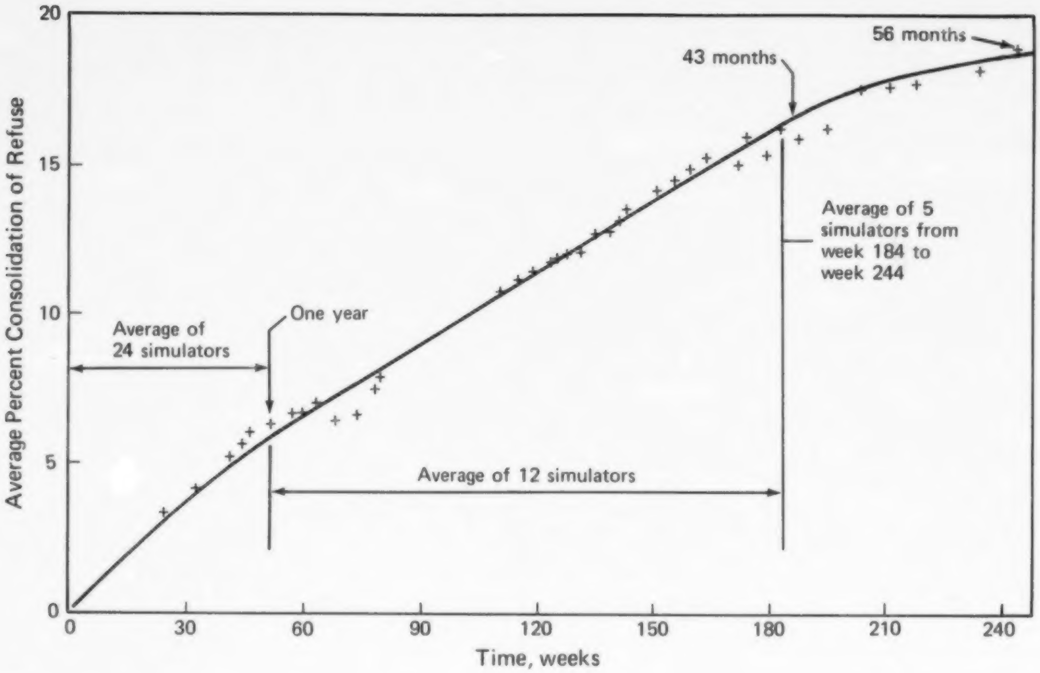

Figure 14. Average consolidation of the refuse in the MSW landfill simulators.

little changed. However, pieces of rubber, such as rubber bands, were highly swollen and some pieces of what appeared to be polyvinyl chloride, such as used in wallets, had become extremely hard. The moisture content of the refuse taken from the generators was found to be about 60%. Facts regarding the refuse in the simulators are given in Table 13.

The refuse in Simulators 11 and 12 was inspected at 43 months and showed little change from that at 12 months. It did appear somewhat more dense and compact but not any more deteriorated. At 56 months, the condition of the refuse had not visibly changed. As at 12 months, newsprint was quite readable and much of the original color in paper and plastic waste appeared to have been retained. Measurements of the water content of the drained waste in three simulators was 59.3, 54.8, and 58.9%, averaging 58.9%

Performance of Simulators and Materials of Construction

The overall design of the MSW landfill simulators worked out well during the 56 months of operation. This design, shown in Figure 2, consisted basically of a ten-foot high, two-foot diameter steel pipe, which contained shredded refuse, mounted on a concrete base in which the liner specimens were sealed to prevent their being bypassed by the leachate.

TABLE 13. INFORMATION ON THE REFUSE IN SIMULATORS

Estimated Refuse Content of a Single Simulator
(Average values)

	Total	Moisture
Amount of shredded refuse as received[a], lb	950	118
Water added to aid compaction, lb	440	440
Water added to bring refuse to field capacity, lb	312	312
Total	1692	820
Calculated moisture content of the refuse at field capacity, %	48.5	...
Initial volume of refuse in a simulator, cu ft	25.1	...
Density at time refuse reached field capacity, lb/cu yd	1820	...
Density at time refuse reached field capacity, lb/cu ft	67.4	...
Moisture content of refuse taken from Simulator 17 after one year of operation, %	59.5	...

[a] Shredded refuse received containing about 12.1% moisture was added in lifts of 20 pounds each. The first few lifts of 30 pounds could not be compacted; therefore, the size of the lifts was reduced to 20 pounds and about one gallon of water added to each.

The conditions that existed in the refuse at the surface of the liners appeared to simulate well the anaerobic conditions which a liner would encounter at the bottom of a MSW landfill. Anaerobic conditions existed during almost the entire exposure period, except perhaps for the first few days. The seals of the pipes to the bases, made of neoprene sponge and butyl caulk, were airtight and showed no indication of leakage when the simulators were dismantled. During the exposure, the temperature was generally cool and ranged from 10 to 20°C.

The leachate drained well through the refuse; drainage through the sand above the liner was good in all simulators until near the end of exposure. Collection of leachate slowed down in one simulator, but did not stop. Examination of the drainage system on opening the simulators at 56 months showed that many slots in the drain pipes in the bases over the liner were plugged by a build-up of cementitious material. This build-up also developed in the sand above the square-woven glass fabric which was placed above the slotted drain pipe. This build-up would indicate that there soon may have been a problem with leachate drainage and collection if the simulators had been left in operation longer than 56 months. The use of filter fabrics over the drain pipe may be the solution for a future design, though they too may become clogged with fines or suspended material in the leachate.

At the beginning of the operation of the simulators, we used standpipes to indicate the level of the leachate within the simulators and collected the leachate on a biweekly basis. The pipes quickly became opaque, so the level of the leachate was difficult to see. Also the time to collect the leachate varied considerably from simulator to simulator and to maintain a constant head on the liner required many collections. Consequently, we changed the method of draining and collecting the leachate to maintain a constant head of one foot of leachate on the liner. A "U" tube was installed in the line so that a one-foot head of leachate could be maintained on the liner and at the same time the leachate could drain continually from the simulators into plastic bags. This was made possible through the use of bags made of polybutylene which could remain full over a period of time without failing. We had initially started with polyethylene bags, but found that they failed at the edges of heat-sealed seams in a relatively short time when filled with leachate because of the stress on the seams. The modification in the collection procedure resulted in a considerable change in the appearance of the leachate that was collected. In the initial procedure, the leachate remained in an anaerobic environment in the simulator and when drained was generally a clear yellow to green solution. The leachate collected continually in the second procedure was a dark brown to black solution.

The polyethylene used to line the two-foot steel pipes worked out satisfactorily. Little water appeared to have come into contact with the steel pipes as almost no rust was generated except near the top of the pipes where air was available.

The epoxy coating (Concresive 1170) used to cover the interior of the concrete bases showed no signs of softening or of failure from the concrete. The coating, however, stained. The epoxy resin (Concresive 1217) used in preparing the rings for sealing the liners in place swelled at the surface and disintegrated in several cells during the exposure period causing bypassing of the liner in four bases. This particular epoxy resin was selected because of its rapid cure, but we now find that epoxies of this type are sensitive to moisture and to off-ratios when combining the two parts. The supplier (Adhesive Engineering Company) has since developed much more chemically resistant epoxy coating and casting resins (Concresive 1305 and 1310). The polyvinyl chloride pipe and valve system worked satisfactorily.

The column containing the refuse was removed with relative ease from the base without damage to the liner or to the specimens buried in the sand above the liner.

EXPOSURE OF ADMIXED LINER MATERIALS IN MSW LANDFILL SIMULATORS

The test results and observations on each of the four primary admixed liner materials exposed to MSW leachate in the simulators are presented and discussed in this section. Test data were obtained on unexposed liner materials and on specimens that had been exposed for 12 and 56 months in the landfill simulators. The recovery of the specimens is described above and detailed data are presented in Appendixes B-1 and B-2.

Paving Asphalt Concrete

During the 12 months of operation of the first set of simulators to be dismantled, leachate was collected below the liner in the base of the simulator that contained the paving asphalt concrete specimen (Table 12). On flooding and pressurizing the base after the column of waste was removed, bubbling occurred at the center of the specimen, confirming the leakage; no bubbling occurred around the periphery. During the 56 months of operation of the second simulator that contained the paving asphalt specimen, no leachate appeared below the liner. Cores cut from both exposed specimens yielded lower coefficients of permeability than was measured on unexposed concrete of the same batch, although one core from the center of the specimen removed at 12 months had a significantly higher permeability, indicating the difference in the degree of compaction at the center and edge of the specimen. The test specimens for exposure were two inches in thickness, and were compacted in steel rings outside the bases. In order that there would be no leachate bypassing the liner at the walls, greater compaction effort was used in the wall areas than in the center. These results indicate that thicker asphalt concrete liners or double lifts should be placed to prevent leakage.

Paving asphalt concrete, as did all of the admixed materials, lost considerably in its unconfined compressive strength, as shown in Table 14.

TABLE 14. UNCONFINED COMPRESSIVE STRENGTH OF PRIMARY ADMIXED LINER SPECIMENS BEFORE AND AFTER EXPOSURE TO WATER AND TO MSW LEACHATE

	Paving asphalt concrete		Hydraulic asphalt concrete		Soil asphalt		Soil cement	
Exposure	psi	%	psi	%	psi	%	psi	%
Original strength, psi	2805	100	2715	100	1218	100	1910[a]	100
Water soak for 24 h at 60°C	2230	80	2328	86	180[b]	15[b]	1323[a,b]	69[b]
In simulators for 12 months	423	15	349	13	15	1.2	1188	62
In simulators for 56 months	258	9	172	6	26	2.0	1182	62

[a] Measured on specimen molded according to ASTM D558.

[b] Water soak at room temperature.

The paving asphalt on 12 months of exposure to the leachate retained only 15% of its original value; at 56 months, it retained only 9%. These values are lower than were anticipated from water immersion tests at 60°C. The loss in strength was probably the result of absorption of water and dissolved organics in the leachate which took place over the longer times, and stripping of asphalt from the aggregate.

The asphalt, when extracted from the exposed concrete after 12 months of exposure, was somewhat harder than in the original concrete. The properties of the asphalt extracted from the concrete after 56 months of exposure were very similar to those measured after 12 months of exposure, indicating that very little change in the asphalt occurred during the additional exposure. Asphalt extracted from a concrete specimen of the original batch after 56 months of exposure to air and weather had a viscosity of 37.0 MP at 25°C and a calculated penetration of 21. Thus, the exposure in the simulator was much less severe on the asphalt per se than normal weather, which probably reflects the anaerobic environment at the bottom of a landfill.

Hydraulic Asphalt Concrete

During the 56 months of exposure, no seepage through the liner occurred in either of the simulators containing hydraulic asphalt concrete (HAC); no leaks were found when the liners and the rings were flooded with water at the time the simulators were dismantled and the bases pressurized. The bottom of the cores and the gravel beneath the liners appeared dry. Tests of the cores in the back-pressure permeameter showed no gain in coefficient of permeability.

As in the case of the paving asphalt concrete, the HAC showed a significant loss in unconfined compressive strength during the exposure. At the end of 12 months, the strength had dropped to 13% of the original compressive strength and at 56 months strength had dropped to 6%. The values showed much greater loss than had been anticipated from immersion tests in water of the cores and molded briquets. The loss in strength probably reflects absorption of water and dissolved organics by the asphalt binder and softening over a long period of time. The effects upon the asphalt binder itself, however, were the opposite. The asphalt extracted from the concrete increased considerably in viscosity and decreased in penetration, which, if the asphalt were dry, would have increased the compressive strength because of the hardening. However, both of these values were obtained on the dried asphalt after removal from the aggregate. This aggregate, which was Watsonville granite, basically has good adhesion to asphalt and has good stripping qualities.

Soil Asphalt

During the 12 months of exposure, 12.1 kg of leachate seeped through this lining specimen in the first set of simulators. The epoxy seal was in good condition when inspected after dismantling of the simulator; there was no indication of bypassing of the liner by leachate.

At 12 months, when the first set of simulators was dismantled, the soil asphalt specimen had almost completely disintegrated structurally and great difficulty was encountered in obtaining core samples for tests. It was not possible to recover intact cores, so the test results obtained may not have been typical for the entire liner. The voids ratio was high, ranging from 18 to 32 on the 3 cores measured, compared with 10.3 to 10.5 on the cores tested before exposure. In spite of the high voids, the permeability was much lower than for unexposed cores. Compressive strength was very low on the exposed material and must have been near zero in the portions of the liner where cores could not be obtained. The viscosity of the extracted binder was higher than before exposure, but was still very low, possibly reflecting loss of the low molecular weight fraction used to cut-back the asphalt.

When the simulators were dismantled after 56 months of exposure, sand was scraped aside enough to examine the condition of the liner, which was very soft and had the appearance of stiff mud. Black, soft concretions were around much of the rim and near the drain tube. Also, small concretions were scattered over the surface of the liner. The fabric had been cut past the end of the drain tubes, and the liner was indented, apparently by the rim of the simulator during removal. The epoxy ring was in good condition, though part of it appeared to contain too much gravel.

A black deposit along the drain tube was sticky and tarry. In the pressure-leak test, bubbles formed and rose in the liner and along the epoxy ring within three to four inches of the rim. The leak areas were mostly from areas of oily concretions on the surface. The liner material lost almost all of its compressive strength during exposure to MSW leachate. At the time of compaction, the unconfined compressive strength measured 1218 psi. At the end of a year it measured 15 psi, and at 56 months 26 psi.

A core cut from the center of the specimen was dry. Samples of gravel from the bottom of the core holes appeared wet. When a core, which came from an area where leaks were detected, was tested in the back-pressure permeameter, it was deformed by the confining pressure used in the permeameter. The value determined for coefficient of permeability, approximately 10^{-7}cm sec^{-1}, may not be reliable because of deformation of the specimen.

Asphalt extracted from the bottom half of a core was slightly less viscous than the original SC-800 grade liquid asphalt, and asphalt extracted from the top half of the core was much lower in viscosity than the original. This effect, and the presence of a small amount of oily material in the sand covering the liner, leads to the conclusion that the waste in the simulator must have contained a low-viscosity, nonvolatile, oily substance which contaminated and softened the liner.

Soil Cement

The soil cement liner in the first set of simulators did not leak during the year that it was exposed. The second liner seeped about a quarter of a liter after the first year. After the simulator was dismantled, seepage through the liner was confirmed by pressurizing the base and observing bubbles rising through water ponded above the liner.

When the simulator containing the soil cement specimen was dismantled after one year the liner was in good condition. Excellent core samples were cut from the exposed liner showing continuation of cure during the year of exposure. Satisfactory cores could not be cut from the unexposed soil cement; it was necessary to use molded test specimens for permeability and compressive strength measurements. The compressive strength of the exposed soil cement was 62% of the value of the original molded test specimen. In the preliminary testing, molded test specimens retained 69% on 24-hour immersion in water at room temperature. In laboratory testing, water permeability of the cores of the exposed liner was lower than that of an unexposed molded specimen, 1.5×10^{-8} and 4.0×10^{-7} cm sec^{-1} vs. 1.5×10^{-6} cm sec^{-1}.

When the second simulator containing the soil cement liner was opened after 56 months of operation, a small amount of sand had hardened, mostly along a line extending perpendicular from the middle of the drain tube to the rim. A dark deposit had developed along the drain tube, and most of the slots in the tube were plugged. The epoxy ring around the specimen was in good condition. The liner was hard and similar to portland cement concrete. One small leak, about one inch from the rim, appeared in the liner when it was flooded and air pressure applied from below. This confirmed the small collection of leachate which had taken place during the operation between 12 and 56 months.

Six two-inch diameter cores were cut. Core 1 was cut at the location of the above leak, and included the leak. All cores from this liner were recovered in two or three pieces, and many showed horizontal voids, possibly indicating boundaries between lifts. Core 1, close to the rim, cut into the lower rim and broke off, though there was some soil cement below that point. The hole from the first core did not drain. Water from the other five core holes ran out the bottom drain. The bottoms of all the cores and the gravel underneath appeared wet, though that may have been due to the water used for coring.

Compressive strength of the soil cement liner after 56 months of exposure to leachate was the same as for the liner specimens recovered and tested after one year of exposure (Table 14). Permeability tests of the top and bottom sections of Core 1, which included a leak detected before coring, gave K values of 1.2×10^{-5} and 2.7×10^{-5} cm sec^{-1}, approximately an order of magnitude more permeable than the molded specimen tested originally. For Core 3, a similar value was determined for the bottom section, but the top was less permeable, 4.3×10^{-7} cm sec^{-1}. The latter value is in the same range as the values determined for cores of the liner tested after one year (Haxo and White, 1977).

ASPHALTIC MEMBRANE LINER MATERIALS

The test results and observations of the two asphaltic membranes exposed to leachate are described and analyzed in this section. Neither of the asphaltic membranes allowed any seepage during the operation of the respective simulators, including the simulators that were dismantled after 12 months and those that were in operation for 56 months. Test data are presented in Appendixes B-1 and B-2.

Catalytically-Blown Asphalt

When the catalytically-blown asphalt liner specimen was recovered after 12 months of exposure to leachate in the simulators, it appeared to have been little affected by the exposure. Analysis showed that it contained 2.9% moisture. Its viscosity at 25°C and at a 0.05 shear rate was slightly higher than at the time it was placed, and it had the same softening point as the unexposed specimen. However, to make the tests, the asphalt is heated and the water is removed; consequently, these data do not reflect the properties of the leachate-swollen asphalt.

At 56 months, when the catalytically-blown asphalt liner was uncovered it had a nonhomogeneous appearance. On examination, it was apparent that some areas were quite weak or "cheesy" and cracked easily on bending, while other areas were still tough and flexible. When the liner was examined in the laboratory after 36 days of storage in a sealed polyethylene bag, the differences were less pronounced. Two cheesy areas were identified, one near the rim and one at the free end of the drain tube. The cheesy areas were not as tender as when examined originally. Samples from each of the above weak areas and from a "normal" area were removed to determine the volatiles content and viscosity. The volatile loss of the sample from the weakest area was about three times that of the other two areas. The viscosities at each of the three areas were approximately equal (Table 15).

As the sample must be heated for determining viscosity, water and volatile organic materials are driven off. Effects caused by the presence of water or other volatiles, therefore, are not detected in the viscosity test.

After 56 months of exposure, both softening point and viscosity had increased, indicating that the asphalt had hardened during exposure so far as its properties in the dry state were concerned. The viscosity increase of the liner exposed to leachate was less than for a sample removed from the upper surface of the same lot of asphalt that had remained in the fiberboard carton which had been stored alongside the simulators from the time they were constructed. This indicated that exposure to air resulted in a greater increase in viscosity than did exposure to leachate. While the measurements made in the dry state indicate good retention of properties, the very tender, "short" and "cheesy" condition observed when the liner was first removed causes some concern for the ability of the liner to withstand minor earth movements when it is in a saturated condition existing beneath a landfill.

Asphalt Emulsion on Nonwoven Fabric

As with the catalytically-blown asphalt, the liner based on asphalt emulsion on nonwoven fabric showed no deterioration after one year of exposure to MSW landfill leachate, though analyses showed that it contained 4.8% moisture. The asphalt extracted from this liner, like that extracted from the asphalt concrete and hydraulic asphalt concrete liners, was lower in viscosity after 12 months of exposure to leachate than before exposure. The viscosity at the low shear rate, 0.001 sec^{-1}, was substantially unchanged, indicating a lower shear susceptibility than for the unexposed specimen.

At 56 months the asphalt emulsion liner continued to show no visible deterioration. Analyses showed that this liner had absorbed additional leachate and contained 8% leachate compared with the 4.8% after one year of exposure.

TABLE 15. PROPERTIES OF ASPHALT MEMBRANE LINERS AFTER 56 MONTHS EXPOSURE TO MSW LANDFILL LEACHATE

	Catalytically-blown Asphalt				
	Weak (near drain tube)	Normal	Weak (near rim)	Avg.	Fabric and asphalt emulsion
Volatiles, %					
47 days at 23°C	1.49	1.26	3.71	...	7.32
2 hours at 110°C	1.42	1.46	4.55	...	7.95
Softening point, °C	...	101	...	...	...
Tests on extracted asphalt:					
Viscosity at 25°C, MP					
At 0.05 s^{-1}	18.5	17.8	15.8	17.4	3.1
At 0.001 s^{-1}	162	161	152	158	3.4
Shear susceptibility	0.56	0.55	0.58	0.56	0.03
Penetration at 25°C (calculated from viscosity)	27	27	28	27	53

EXPOSURE OF THE PRIMARY MEMBRANE LINERS

Flexible polymeric membrane liner specimens were subjected to two types of exposure in the landfill simulators, those mounted as barriers in the simulators as the primary test specimens, and those buried in the sand above the barriers as secondary test specimens. The results of testing the primary polymeric membrane liner materials that had been exposed in the landfill simulators are presented in this subsection. The results of the exposure testing of the buried specimens are presented and discussed separately in the following subsection; the results of the immersion testing in leachate and deionized water of the same and other polymeric sheetings are presented in Section 9.

The primary liners were recovered from the simulators after 12 and 56 months of exposure. None of the membrane liners that had been well sealed into the bases of the simulators showed any seepage. The epoxy seals in 3 of the bases containing membrane liners failed during the last year of operation of the simulators. The absence of seepage confirms the very low permeability of the membrane lining materials. The results also show the adequacy of the seams that were placed in the liners.

Exposed liner specimens were cut from the bases while they were still wet and sealed in polyethylene bags to keep them in a moist condition until they were tested. All tests were made on samples as taken from the bases, i.e. none of the samples were dried prior to testing. In all of the bases from which the specimens were cut, the square-woven glass fabric and gravel below the liners were in an "as new" condition, except in the base that contained the CSPE liner, where a small area of the glass fabric was stained. Close examination under magnification of the sheeting immediately above the stain showed that a small piece of foreign material existed in the liner compound, which resulted in a pinhole.

Effect of the Exposure to Leachate on Properties of Membrane Liners

The results of the analyses and physical testing of the specimens before and after exposure are presented in Table 16, with additional details presented in Appendix D. These test results are divided into analyses, physical properties, and seam strength, and are arranged by liner material and by exposure time. All tests on exposed samples were made as soon as possible after removal from service. They were stored under conditions which would not cause changes in properties after removal from service. This procedure results in the determination of properties of the materials as they existed in the actual service environment.

To estimate the amount of leachate absorbed by a liner material, the volatiles content of a sample of the exposed material was measured. The absorption of leachate by a liner can be calculated when the original weight of the specimen is known such as is known when laboratory tests are made. In the field, however, it is necessary to cut a sample from the exposed liner and determine its volatiles content. In such cases, the absorption of leachate also requires information as to the extractables that are lost and the nonvolatiles that are absorbed. Most leachates are essentially volatile, except for minor amounts of inorganic dissolved salts. The CSPE, CPE, and EPDM liners, in this order, had the highest volatile contents; therefore, they absorbed the greater amounts of leachate. The LDPE, PVC, and butyl liners had the lowest volatile contents and absorbed lesser amounts of leachate.

By comparing the amounts of extractable material in exposed specimens that have been dried, the amount of plasticizer or other ingredients in the compound that was lost to the leachate can be calculated. In all cases, the extractables, after 56 months, were lower than the original extractables. The magnitude of the loss, even in the case of the EPDM and PVC, was in the order of 10%.

The tensile properties of the materials varied; the tensile strength ranged approximately from 1400 to 2500 psi. The changes with exposure time were only modest and many may have been within experimental error, though several showed trends toward increasing values. Tests which reflect the stiffness of the materials, such as modulus, stress at 200% elongation, and hardness, showed a minimum at 12 months. These minima may reflect the changes in the composition of the leachate; at 12 months the leachate concentration showed significantly higher organic content than it did at 56 months. In all cases tear strength and puncture resistance remained at satisfactory levels over the 56 months of exposure.

TABLE 16. EFFECT ON PROPERTIES OF POLYMERIC MEMBRANE LINERS OF 12 AND 56 MONTHS EXPOSURE TO LEACHATE IN MSW LANDFILL SIMULATOR

Item	Test method	Exposure time, months	Butyl rubber	CPE	CSPE	EPDM	LDPE	PVC
Type of compound[a]	...	...	XL	TP	TP	XL	CX	TP
Liner number[b]	...	...	7	12	6R	16	21	17
Simulator number, 0-12 months	...	...	21	24	22	23	19	20
0-56 months	...	...	3	6	4	5	1	2
Analytical properties								
Volatiles (2 h at 105°C), %	...	0	...	0.10	0.29	0.50	0.00	0.09
	...	12	2.02	6.84	12.78	5.54	0.02	3.55
	...	56	2.37	7.61	13.90	5.74	1.95	2.08
Extractables after removal of volatiles, %	ASTM D3421, modified	0	11.0	7.5	3.8	31.8	...	37.3
		56	9.8	5.1	3.4	28.3	3.37	34.4
Solvent[c]	...	...	MEK	n-heptane	DMK	MEK	MEK	CCl_4+ CH_3OH
Physical properties								
Thickness, mils	...	0	63	32	36	51	12	21
		12	64	35	38	51	11	21
		56	64	37	37	49	10	22
Tensile strength[d], psi	ASTM D412	0	1435	2275	1765	1480	2145	2580
		12	1395	1810	1640	1455	2465	2350
		56	1465	1960	2110	1460	2585	2740
Elongation at break[d]	ASTM D412	0	400	410	250	415	505	280
		12	410	400	300	435	505	330
		56	405	385	235	375	540	340
Tensile set[d], %	ASTM D412	0	17	430	115	12	370	73
		12	14	210	105	12	430	57
		56	12	160	60	6	410	62
Stress at 200%[d], psi	ASTM D412	0	695	1330	1525	755	1260	1965
		12	685	1090	1245	740	1205	1550
		56	750	1140	1825	800	1325	1810
Tear strength (Die C)[d], ppi	ASTM D624	0	175	255	...[e]	180	390	335
		12	200	320	...	195	495	450
		56	185	170	...	130	405	285
Hardness, Durometer points, 10 second reading	ASTM D2240	0	51A	77A	79A	54A	...	76A
		12	50.5A	65.5A	64A	51.5A	...	64A
		56	51A	70A	70A	51A	...	70A
Puncture resistance[f]	FTMS 101B Method 2065							
Stress, lb		0	44.8	47.0	32.9	39.4	13.9	25.8
		12	49.5	49.8	57.0	40.1	14.8	30.1
		56	50.0	51.8	58.2	41.5	17.1	31.3
Elongation, in.		0	1.22	1.04	0.60	1.44	0.76	0.69
		12	1.20	0.98	0.88	1.18	0.80	0.70
		56	1.25	0.98	0.86	1.19	1.24	0.84

See footnotes at end of table.

TABLE 16 (Continued). EFFECT ON PROPERTIES OF POLYMERIC MEMBRANE LINERS OF 12 AND 56 MONTHS EXPOSURE TO LEACHATE IN MSW LANDFILL SIMULATOR

Item	Test method	Exposure time, months	Butyl rubber	CPE	CSPE	EPDM	LDPE	PVC
Seam strength								
Location of seam preparation	...	...	Lab	Lab	Lab	Factory	Lab	Factory
Bonding system	...	...	Adhesive (LVT)[g]	Solvent THF:Toluene 50:50	Cement	Adhesive (LVT)[g]	Heat	Cement
Peel strength, avg, ppi	...	0	3.8	10.0	>30.0[h]	5.4	15.6[h,i]	4.0
		12	2.9	5.2	3.4	2.0	...	5.1
		56	3.4	2.9	1.8	7.1	12.0[i]	5.6
Shear strength, ppi	...	0	30.0	>57.0[h]	>50.0[h]	44.5	>20.2[h]	27.2
		12	42.0	>35.0	40.2	24.3	>11.4[h,j]	>25.6[h]
		56	17.0	17.0	10.0	18.0	11	>22[h]

[a] XL = Crosslinked; TP = thermoplastic; CX = partially crystalline thermoplastic.

[b] Contractor's serial number. R indicates liner is fabric reinforced.

[c] Solvents used in extraction: DMK = acetone, MEK = methyl ethyl ketone, CCl_4+CH_3OH = 2:1 blend of carbon tetrachloride and methyl alcohol.

[d] Average of values in machine and transverse directions.

[e] Test method not applicable to fabric-reinforced materials.

[f] Rate of penetration of probe: 20 inches per minute.

[g] Low temperature curing cement.

[h] Break in specimen outside of seam.

[i] Seam failed at initial peak.

[j] Seam in the polyethylene liner used in the steel pipes; tabs in the liner specimens mounted in base were too short.

Though the sheetings showed good retention of properties during exposure, there was a significant drop in several cases in the seam strength of the materials. This showed up in the CPE, CSPE, and EPDM specimens, though this loss of adhesion did not result in any seepage or leakage of the liner specimens. The fact that there was no leakage may have been due to the lack of stress on the specimens. The simulators were designed not to allow any stress on the specimens because of doubts that stress could be controlled.

Overall, the changes in the physical properties of the membranes resulting from 56 months of exposure were relatively minor. All of the membranes softened to varying degrees during the first 12 months. This change is probably due to the swelling by the leachate. In the interval of time to 56 months, the PVC, CSPE, and CPE membranes rehardened slightly, possibly indicating, in the case of the PVC membrane, loss of plasticizer and, in the case of the CSPE and CPE membranes, crosslinking of the polymers. They all recovered most of their tensile properties that were lost due to the initial softening. These materials were all thermoplastic and unvulcanized.

Of the six polymeric membranes, the LDPE film best maintained original properties during the exposure period as shown in Table 16; it also absorbed the least amount of leachate. However, this membrane, which was 10 mils in thickness, probably has too low a puncture resistance for use in lining a landfill. This deficiency was confirmed in handling it in the lining of the steel pipes of the simulators, in the preparation of the primary liner specimens, and in the making and use of the LDPE leachate collection bags. The butyl and EPDM liners changed slightly more in physical properties than did the LDPE liner during the exposure period.

The fact that, except in the bases in which the epoxy resin sealing ring deteriorated, no leachate appeared below the membrane liners during the exposure period indicates that the very low permeability of the polymeric membranes is maintained after extended exposure to MSW leachate.

EXPOSURE OF BURIED SPECIMENS

The specimens buried in the simulators were strips approximately 2.125 in. by 20 in. A two-inch lap seam joint was incorporated at one end of most of the specimens. Those with joints were prepared as 4.5-inch wide strips which were cut in half and then trimmed so that none of the adhesives covered a specimen edge. All the specimens were spirally coiled and buried vertically in the sand above the primary liners so that there could be flow through the specimems. The coiled strips were distributed among the 16 simulators in which the polymeric and asphaltic membrane specimens were mounted. Two sets of 42 strip specimens, differing in liner number or in bonding system, were buried 5 or 6 to a simulator. A list of all the specimens buried in the simulators is presented in Table 17. The table also lists, by sheeting, the simulators in which the test specimens were buried, the exposure periods, and the number of seaming systems exposed.

When the simulators were dismantled, the individual strip specimens were flushed with water to remove the sand and loose material. The specimens were placed into long, polyethylene bags, which were then closed by heat-sealing to keep them moist until testing. Two tensile dumbbells, two tear specimens, one puncture specimen, and two adhesion specimens, one for peel and one for shear tests, were cut from most of the strips and tested. The testing was limited by the size of the exposed specimen; however, the number of both exposures and specimens were enough to indicate trends.

Effect of the Exposure on Properties

The results of testing the exposed specimens are presented in Appendixes E, F, and G. The exposures were for 12, 13, 43, or 56 months, depending upon when the specimens were buried and recovered. The data for the 13 months are included in Appendix G with the 56 months data because the 13 months specimens were buried in the sand in two simulators at 43 months when the simulators were opened to examine the primary asphalt membrane liner specimens.

In all cases, there was an absorption of leachate by the individual specimens as measured by the increase in volatiles over the original volatile contents. The values, however, varied considerably depending partially on the material. For example, the CPE and CSPE samples tended to have high absorption of the leachate. Other materials, such as butyl, polyethylene, and the PVC's, had low absorption values. Generally, there was a reduction in the amount of extractable components in the individual specimens after they were dried, indicating that constituents of the original compounds, particularly oil and plasticizer, degraded or migrated into the leachate during exposure.

The effects on the physical properties, as in the case of the primary liners, was modest. None of the commercial polymeric liner materials tested showed a drastic loss in properties, even after 56 months of exposure. Generally, there were small losses in tensile strength and in modulus. There appears to be a maximum or minimum of many of the properties at 12 months compared with the 56-month data, which indicates the possible effect of the higher organic content of the leachate at 12 months of generation.

As can be seen from the data in Table 18, the PVC membranes vary considerably in initial composition and properties. For example, the plasticizer contents of five PVC membranes, as measured by extractables, varied from 32.3 to 38.9%. In tensile strength, the variation among nine different PVC membranes was from 2435 to 3400 psi and elongation at break ranged from 200 to 385%. The retention values also varied considerably among the different PVC membranes, showing a possible difference in the migration of the plasticizer out of the compounds. These results indicate that recognition should be given to this variation in the selection of liners for specific applications.

Of particular interest are the variations in the leachate absorption by different liners of the same type polymer. In the case of the PVC membranes, the absorption ranged from 0.37% to 6.75%. In the case of the CSPE membranes, swelling ranged from 8.7% to 21%. EPDM varied from 5.1% to 9% in leachate absorption.

Miscellaneous Materials

In addition to the buried specimens of polymeric membrane liners, samples of a variety of other materials were also buried in the simulators, principally in Simulators 11 and 12. These materials included:

TABLE 17. SPECIMENS BURIED IN THE SAND ABOVE THE PRIMARY LINERS IN THE SIMULATORS

Liner number	Polymer	Number of bonding systems	Simulator number[a]	Exposure time, months 12	13	43	56
3	Chlorosulfonated polyethylene	2	2(2),20(2)	x			x
4R	Chlorosulfonated polyethylene	2	2(2),20(2)	x			x
5	Asphalt roofing felt	0	3,21	x			x
6R	Chlorosulfonated polyethylene	1	4,22	x			x
7	Butyl rubber	1	3,21	x			x
8	Ethylene propylene rubber	1	11,17	x		x	
9	Neoprene	1	2,20	x			x
10	Polyvinyl chloride	1	1,19	x			x
11	Polyvinyl chloride	1	1,19	x			x
12	Chlorinated polyethylene	4	4(4),22(4)	x			x
13R	Chlorinated polyethylene	4	6(4),24(4)	x			x
14R	Chlorosulfonated polyethylene	1	3,21	x			x
15	Polyvinyl chloride	1	11,17	x		x	
16/18	Ethylene propylene rubber	1	5,23	x			x
17	Polyvinyl chloride	2	11,17	x		x	
19	Polyvinyl chloride	2	1(2),19(2)	x			x
20	Polybutylene	1	1,19	x			x
22	Butyl rubber	1	3,21	x			x
23	Chlorinated polyethylene	4	5(4),23(4)	x			x
24	Butyl rubber	1	3,21	x			x
25	Ethylene propylene rubber	1	6,24	x			x
26	Ethylene propylene rubber	1	12,18	x		x	
27	Polypropylene	0	11,17	x		x	
28	Thermoplastic rubber	0	11,17	x		x	

See footnotes at end of table.

TABLE 17 (Continued). SPECIMENS BURIED IN THE SAND ABOVE THE PRIMARY LINERS IN THE SIMULATORS

Liner number	Polymer	Number of bonding systems	Simulator number[a]	Exposure time, months			
				12	13	43	56
29	Thermoplastic rubber	0	12,18	x		x	
30	Natural rubber gasket	0	12,18	x		x	
31	Styrene butadiene rubber gasket	0	12,18	x		x	
32[b]	Urethane rubber gasket	0	12,18	x		x	
33[b]	Neoprene solid gasket	0	11,17	x		x	
34[b]	Neoprene sponge gasket	0	12,18	x		x	
36[b]	Elasticized polyolefin	1	11		x		
38[b]	Chlorinated polyethylene	1	12		x		
67[b]	Polyvinyl chloride	1	11		x		
82[b]	Neoprene	0	12		x		
88[b]	Polyvinyl chloride	0	12		x		
92A[b]	Polyvinyl chloride	1	12		x		
93[b]	Polyvinyl chloride	0	11		x		
94[b]	Ethylene propylene rubber	0	11		x		
98[b]	Polybutylene	1	12		x		
99[b]	High-density polyethylene	1	11		x		

[a] Number of simulator in which specimens were buried. Number in parentheses is the number of specimens of a given liner number.

[b] Buried in sand in Simulators 11 and 12 at 43 months.

- An asphalt roofing felt based on fiberglass (in Simulators 3 and 21).
- A polypropylene.
- Two thermoplastic rubbers of different stiffness.
- A natural rubber gasket.

TABLE 18. PROPERTIES OF PVC MEMBRANE SPECIMENS BEFORE AND AFTER EXPOSURE TO LEACHATE IN MSW LANDFILL SIMULATORS

Specimen number[a]	10	11	15	17	19	67	88	92A	93
Simulator number	1	1	11	11	1	11	12	12	11
Nominal thickness, mils	34	31	11	20	21	21	20	22	11
Exposure time, months	56	56	43	43	56	13	13	13	13
Analytical properties:									
Volatiles, %									
Initial	0.30	0.11	0.47	0.08	0.05	0.03	0.17	0.23	0.12
Final	6.32	1.97	1.92	2.10	0.51	0.66	0.67	1.29	1.73
Change	+6.02	+1.86	+1.45	+2.02	+0.46	+0.63	+0.50	+1.06	+1.61
Extractables, %									
Initial	32.54	33.90	...	37.25	38.91	...	33.46	...	32.26
Final	30.53	31.37	33.33	34.39	36.13	36.25	30.64	30.72	29.34
Change	-2.01	-2.53	...	-2.86	-2.78	...	-2.82	...	-2.92
Physical properties:									
Thickness, mils									
Initial	32	30	10	20.5	22	22	20	20	11
Final	34	31	11	20	24	21	20	21	11
Change	+2	+1	+1	-0.5	+2	-1	0	+1	0
Tensile at break[b], psi									
Initial	3400	3140	2360	2640	2780	3020	3395	2435	3035
Final	3140	2955	2180	2760	2765	2995	3590	2655	3145
Retention, %	92	94	92	105	100	99	106	109	104
Elongation at break[b], %									
Initial	280	325	200	270	330	385	325	245	350
Final	330	315	280	380	340	345	310	335	315
Retention, %	118	97	140	141	103	90	95	137	90
S-200[b], psi									
Initial	2610	2295	2360	2080	1890	1820	2610	2170	2055
Final	2420	2355	2000	1800	2020	2150	2730	1895	2410
Retention, %	93	103	90	87	107	118	105	87	117
Tear resistance[b] (Die C)									
Initial	390	380	295	352	295	340	460	435	362
Final	450	425	380	385	345	360	560	420	390
Retention, %	115	112	129	109	117	106	122	96	108
Hardness, Duro A, 10 sec. rdg.									
Initial	82	80	72	76	72	75	80	82	78
Final	85	85	69	72	75	73	78	75	75
Change	+3	+5	-3	-4	+3	-2	-2	-7	-3
Puncture strength (20 ipm)									
Stress, lb									
Initial	42.9	39.5	12.8	25.8	24.0	27.8	28.6	27.4	15.9
Final	61.2	59.7	15.4	29.6	35.9	35.1	34.0	33.4	18.9
Retention, %	143	151	120	115	150	123	119	122	119
Elongation, in.									
Initial	0.62	0.62	0.61	0.69	0.71	0.68	0.56	0.62	0.55
Final	0.78	0.80	0.70	0.88	0.80	0.78	0.68	0.74	0.56
Retention, %	126	129	115	128	1.13	115	121	119	102

[a] Contractor's identification number.

[b] Tensile and tear properties in machine direction only except for No. 93 which is reported in transverse direction only.

- A styrene butadiene rubber (SBR) gasket.
- A urethane rubber gasket.
- Two neoprene gaskets, one solid and one sponge.

The test data on these materials, before and after exposure to MSW leachate, are presented in Table 19 and in Appendixes E and F.

The roofing felt was originally considered as a possible candidate liner but, because of its stiffness, brittleness, and very low elongation at break, it was discarded as a primary liner. Consequently, only small pieces of this material were buried in 2 simulators. They did not have seams. The asphalt roofing felt absorbed more than 15.5 % leachate during the 56 months, after having absorbed 13.4% in the first year. It retained its original propertes; that is, it had low elongation, ca. 10%, was brittle, and broke on bending. The puncture resistance changed little.

Polypropylene was discussed in 1973 as a potential liner material in spite of its stiffness; no liner membrane of this polymer has been made commercially. The test specimens were cut from a sheet of unpigmented (no carbon black) material obtained from a local plastics vendor. The polypropylene absorbed little leachate, 0.2-0.4%, and retained its properties well for the 43 months. However, it did change somewhat; tensile strength fell, but modulus and tear strength increased.

The two thermoplastic elastomer samples were cut from molded slabs prepared in our laboratory. The thermoplastic elastomers differed in the effect of leachate, the more stiff version swelled little and retained its properties better than did the softer version which softened. Polymeric materials of this type appear to have a potential for use as liners.

Of all the polymeric materials tested in the project, the urethane gasket material suffered the greatest loss in properties. The urethane deteriorated drastically in 43 months of exposure, falling in tensile strength from more than 5000 psi to 370 psi and in elongation at break from 550% to 100%. The deterioration was probably caused by the hydrolysis of the polymer which was probably a polyester. This behavior indicates a potential problem with urethane rubber which has been used in some lining materials; however, urethanes vary greatly and some are quite resistant to moisture and hydrolysis. The deterioration of the urethane sample simply points out that some polymers are quite sensitive to a humid environment and that care must be taken in the selection of polymers for use in such environments.

The natural rubber gasket material softened considerably during the exposure, as did the styrene butadiene rubber gasket material. Both neoprene gasket materials softened and lost in tensile strength. Again, these results show the importance of both polymer type and compounding on performance in a moist environment.

COMPARISON OF RESULTS ON BURIED AND PRIMARY LINER SPECIMENS

An important objective of this study of buried specimens of liners was to determine whether this type of exposure would correlate with that of the primary liners.

TABLE 19. EFFECTS OF EXPOSURE TO MSW LEACHATE ON BURIED SPECIMENS OF MISCELLANEOUS MATERIALS

Polymer		Polypropylene			Natural rubber gasket			Urethane rubber gasket			Neoprene gasket					
											Solid			Sponge		
Identification number		27			30			32			33			34		
Exposure time, months		0	12	43	0	12	43	0	12	43	0	12	43	0	12	43
	Direction of test															
Properties																
Thickness, mils (avg. 3 readings)		9-12	10	10.5	146-148	151	166	47-62	63	61.5	125-137	147	116.0	245-248	201	183.5
Volatiles content (moisture), %		...	0.40	0.19	0	6.02	5.79	...	2.21	1.53	...	8.94	12.54	...	44.45	54.30
Tensile strength, psi	Machine	6590	6560	6040	2870	1280	2200	>5000	1390	370	1550	1000	550	65	100	140
Elongation at break, %	Machine	860	825	650	775	650	700	620	550	100	720	575	450	220	250	280
Set after break, %	Machine	710	595	320	14	6	10	4	19	2	27	11	5	36	58	40
S-100, psi	Machine	2650	3040	3240	75	100	105	620	440	375	110	90	80	37	50	50
S-200, psi	Machine	2760	3120	3440	140	150	165	810	560	...	190	170	160	62	80	105
S-300, psi	Machine	2740	3200	3440	220	210	245	1280	635	...	270	270	260	...	...	...
Tear strength, ppi		775	960	1020	...	...	150	392	...	100	...	...	...	...	...	...
Hardness, Durometer points, 10 sec. reading		95A	82A	90A	50A	35A	36A	75A	77A	57A	49A	31A	27A	...	...	...
Puncture strength																
Stress, lbs		16.9	20.5	19.2	...	...	59.2	...	...	14.0	...	...	42.0	...	...	...
Elongation, in.		0.48	0.68	0.68	...	...	0.68	...	...	0.42	...	...	1.64	...	...	...

The physical properties of four buried specimens exposed for 56 months are compared in Table 20 with properties of the same materials exposed for the same length of time as primary specimens. Inasmuch as the buried specimens contacted the leachate on both sides, the effects of the exposure to leachate could be expected to be greater than that encountered by the primary specimens which contacted the leachate from only one side. The results show that, in three of the four cases, the amount of leachate absorbed by the buried specimens was greater than the amount absorbed by the primary specimens; in the fourth case, the butyl specimen, the absorption of leachate was essentially the same.

With respect to the effects upon physical properties, the results varied among the four materials. Overall, however, the buried samples tended to soften more than the primary samples. The major difference between the results of the two exposures was in retention of seam strengths of some of the membranes. This probably reflects the differences in the preparation of the test specimens. For example, the adhesion of the buried CSPE sample was significantly better than that of the primary sample; on the other hand, the reverse was true of the EPDM specimens.

Although there is some variation in the results, the data indicate that specimens immersed in a landfill can indicate the effects of leachate and can be used as a measurement of the effects of leachate on liners.

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TABLE 20. COMPARISON OF PROPERTIES OF PRIMARY AND BURIED SPECIMENS AFTER 56 MONTHS OF EXPOSURE TO LEACHATE IN THE MSW LANDFILL SIMULATORS

Polymer	Butyl		CPE		CSPE		EPDM	
Specimen number[a]	7		12		6R		18	
Nominal thickness, mils	63		31		34		51	
Type of compound[b]	VZ		TP		TP		VZ	
Thread count, ends per inch (epi)	...		...		8 x 8		...	
Type of specimen	Primary	Buried	Primary	Buried	Primary	Buried	Primary	Buried
Analyses:								
Volatiles (2 h at 105°C), %	2.37	2.02	7.61	10.1	13.9	17.0	5.74	6.47
Extractables, %	9.76	9.79	5.09	5.73	3.35	3.84	28.3	30.0
Solvent[c]	MEK		nC_7H_{16}		DMK		MEK	
Physical properties[d]:								
Tensile strength of fabric, ppi	...	...	...	...	37	41	...	...
Tensile strength of polymer, psi	1490	1510	2270	2205	1980	2620	1520	1505
Elongation at break, %	420	435	360	295	220	200	380	495
Set after break, %	12	16	160	165	50	53	5	15
S-100, psi	320	300	1060	1165	800	1245	350	295
S-200, psi	720	680	1460	1665	1670	2620	860	655
S-300, psi	1160	1090	1910	2185	...	...	1240	975
Tear strength, Die C, ppi	185	185	180	215	...	...	135	175
Hardness, Durometer points 10 sec. reading	51A	53A	70A	64A	70A	67A	51A	47A
Puncture strength:								
Thickness of specimen, mils	64	66	37	38	37	40	49	58
Stress, lb	50.0	38.0	51.8	49.3	58.2	57.4	41.5	41.5
Elongation, in.	1.25	1.14	0.98	0.97	0.86	0.84	1.19	1.42
Seam strength:								
Bonding system	Cement 8800 (lab)		Solvent, 50 THF[e]: 50 Toluene (lab)		Cement 280Z (lab)		Solvent 374+ Cement MAG (fac)	(lab)
Shear, ppi:	17	39.5	17	...	10	6.92	18	14.9
Locus of failure[f]	AD-LS	AD	LS	...	AD-LS	SE	AD	AD
Peel:								
Average, ppi	3.4	3.0	2.9	2.0	1.8	16.0	7.1	0.4
Maximum, ppi	3.8	4.2	4.5	2.6	3.2	22.8	7.6	0.7
Locus of failure[f]	AD	AD-LS	LS	LS	AD-LS	AD	AD	AD

[a] Contractor's identification number. R = fabric reinforced.

[b] VZ = Vulcanized; TP = Thermoplastic.

[c] Solvent: MEK = Methylethyl ketone; DMK = Dimethyl ketone = Acetone; nC_7H_{16} = n-heptane.

[d] Tensile properties all in machine direction.

[e] THF = Tetrahydrofuran.

[f] Locus of failure code:
AD = Failure within the adhesive.
AD-LS = Failure between adhesive and liner surface.
LS = Failure at liner surface.
SE = Failure at seam edge.

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EPA Form 2350-4 (4-80)
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SECTION 9

EXPOSURE TESTING OF POLYMERIC MEMBRANES BY IMMERSION IN MSW LEACHATE AND IN WATER

IMMERSION OF MEMBRANE LINERS IN MSW LEACHATE

The results of tests performed on buried strips of membrane materials exposed for one year were similar to those of the primary liners exposed for the same length of time. This similarity indicated that the complete immersion of a specimen in leachate would be a feasible method of exposing liners for test purposes (Haxo, 1979). Furthermore, the availability of the leachate generated in the MSW landfill simulators made it possible to perform immersion tests using the same liquid used in the exposure testing of both the primary and the buried specimens. Thus we had the opportunity to develop correlation among three types of exposure conditions.

Consequently, the study was expanded to include the immersion exposure of specimens of polymeric membranes in MSW leachate. Three sets of slab specimens of 28 different sheetings were immersed in MSW leachate generated by the simulators so that testing could be performed after three exposure intervals. Also, because MSW leachate is principally water, which by itself can be aggressive to many materials, water absorption tests were performed on a series of membrane liner materials. These tests are discussed in the subsequent sections.

We attempted to run similar exposure tests with admix specimens but found that in their unconfined state they crumbled apart when hung in the leachate. Immersion testing of the admixes and of the asphalt membranes was, therefore, abandoned.

The Immersion System

Our first design was to attach small cells or bags containing the liner specimens directly to the individual leachate simulators and allow the leachate to flow by the specimens while being continuously drained. Such a design would maintain the anaerobic condition that existed in the simulator where the primary liners were being exposed. However, the leachates being produced by the individual simulators differed in composition from one another enough to become a possible experimental factor. Furthermore, the design also required both a large number of containers and monitoring of the 12 simulators with the attached containers which posed a variety of problems and additional effort.

The design we finally selected for an immersion system allowed a blend of the leachates from the 12 simulators to flow slowly through a series of polyethylene tanks in which the membrane slab specimens were hung. We felt this arrangement was acceptable because of the low permeability of the polyethylene to air. We confirmed this by storing samples of leachate in polyethylene containers at room temperature and observing only small changes in the composition of the leachate over a period of one month. Furthermore, this design allowed easy exposure of more specimens, all to the same leachate, and required a relatively small amount of time to construct and monitor.

For the immersion cells, we selected heavy-duty high-density polyethylene (HDPE) tanks, 14 x 10 x 10 in. in dimensions, each with a six-gallon capacity. The size of the tank was sufficient to allow immersion of 8 x 10 in. slab specimens from which enough test specimens could be cut to measure the desired number of physical and analytical properties. Stainless steel hooks, from which the specimens were to hang 0.92 in. apart, were sealed into the lids of the tanks. Inlets and outlets were also installed. The lids, with the specimens hanging from them, were then welded onto the tanks. A schematic drawing of an immersion tank is presented in Figure 15.

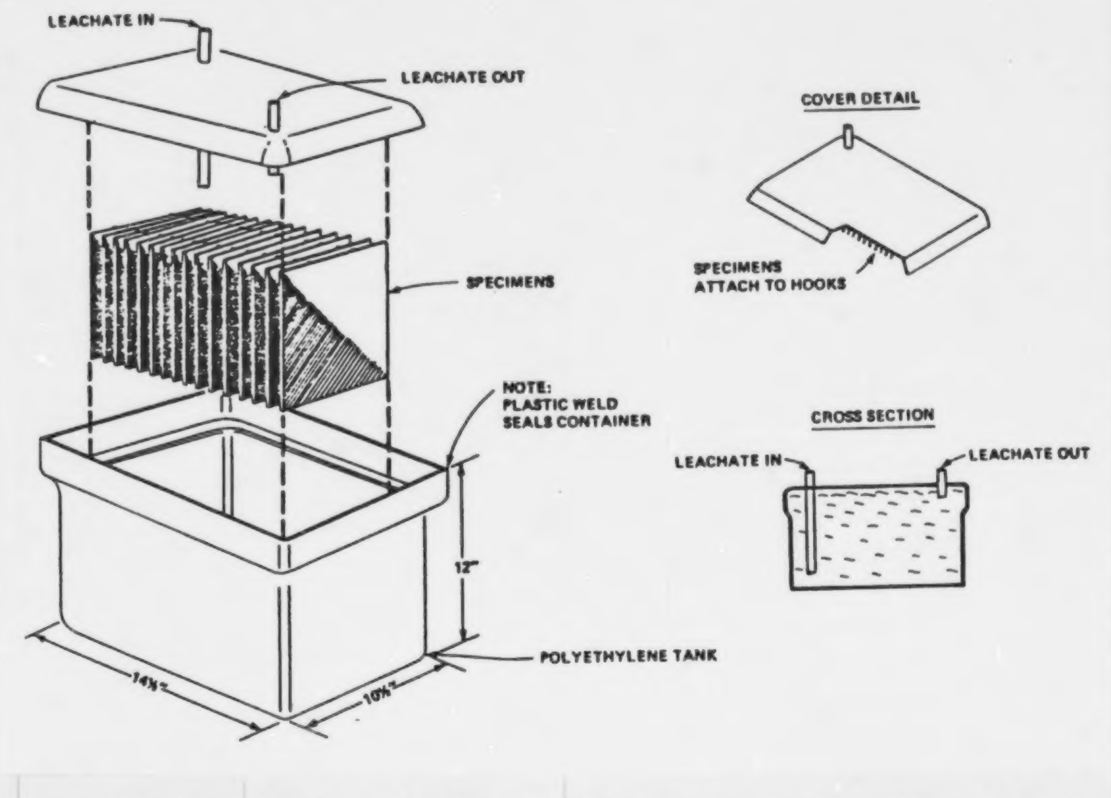
LEACHATE IN
LEACHATE OUT
COVER DETAIL
SPECIMENS
SPECIMENS ATTACH TO HOOKS
NOTE: PLASTIC WELD SEALS CONTAINER
CROSS SECTION
LEACHATE IN
LEACHATE OUT
12"
POLYETHYLENE TANK
14½"
10½"

Figure 15. Individual polyethylene immersion tank, showing method of holding specimens and the inlet and outlet for the leachate.

Initially, the flow of the leachate through the tanks was effected by gravity feed from a drum containing leachate placed above the tanks. Problems were encountered with this arrangement; solids precipitated from the leachate and plugged the system. We then installed a Masterflex pump that delivered leachate at the rate of 14 mL per minute through the tanks. The supply of leachate recirculated in about 12 days.

Selection of Polymeric Membranes for Testing

Twenty-eight different membranes of 11 polymeric types were selected for immersion testing. Table 21 lists the number of different sheetings by polymer type. The materials selected included some that were already in exposure in the simulators as well as others that had become available either commercially or on a developmental basis. Three sets of the 28 liner specimens were immersed so that specimens could be tested after six, twelve, and eighteen months of immersion. Later these times were changed to eight, nineteen, and thirty-one months. No attempt was made to seal the exposed fabric ends of the fabric-reinforced sheetings.

TABLE 21. LINERS IMMERSED IN MSW LEACHATE

Type of polymer	Number of different sheetings immersed
Butyl rubber (IIR)	1
Chlorinated polyethylene (CPE)	3
Chlorosulfonated polyethylene (CSPE)	3
Elasticized polyolefin (ELPO)	1
Ethylene propylene rubber (EPDM)	5
Neoprene (CR)	4
Polybutylene (PB)	1
Polyester elastomer	1
Low density polyethylene (LDPE)	1
Polyvinyl chloride (PVC)	7
PVC and pitch	1
Total	28

Operation of Immersion System

Approximately 48 gallons of leachate, obtained by blending the output of the 12 simulators remaining after the first set of 12 was dismantled, was introduced into the system every four weeks and a similar amount of the used leachate was drawn off. The new leachate was the accumulation of the two previous biweekly collections, each of 24 gallons, from the simulators. Samples of both the new and used leachate were tested at each addition for: pH, chemical oxygen demand (COD), total solids (TS), total volatile solids (TVS), and total volatile acids (TVA).

The differences in the composition of the leachate added and that of the leachate removed were small, indicating the air-tight, anaerobic character of the system. During the initial operation of the system, the analytical results (Table 22) were close to the calculated averages of the leachates from the simulators. In later months, however, differences developed between the two that may have been caused by biological contamination of the blended leachate. The pH of the leachate from the simulators (Figure 11) increased at a regular rate; however, the pH of the blended leachates removed from the immersion system became substantially higher than the leachate added to the system starting in October-November 1977 and remained high until the conclusion of the project.

TABLE 22. ANALYSIS OF LEACHATE USED IN THE IMMERSION SYSTEM[a]

Property	Leachate added to system	Leachate removed from system
pH	5.27	5.27
Chemical oxygen demand, g/L	32.6	29.0
Total volatile acids, g/L	11.3	11.3
Total solids, %	1.70	1.80
Total volatile solids, %	0.94	1.00

[a] Samples were taken on January 31, 1975.

Some gas was generated in the immersion tanks, which necessitated the addition of relief valves to prevent pressure buildup. During the course of the operation, two leaks developed at the welds and required repairs.

The immersion system was operated from the 24th month of the primary exposure until the end of the project when the simulators were dismantled.

IMMERSION TEST RESULTS

The tests performed on the lining materials before and after each of the three exposure intervals were:

- Weight of specimen.

- Dimensions of specimen.

- Tensile properties, in machine and transverse directions, ASTM D412.

- Hardness, ASTM D2240.

- Tear strength, in machine and in transverse directions, ASTM D624, Die C.

- Puncture resistance, FTMS 101B, Method 2065.

- Volatiles, percent weight loss after two hours at 105°C.

- Specific gravity, ASTM D297 (unexposed liner material only).

Because of the limited size of the exposed slab, fewer specimens for tensile, tear, and puncture were tested than called for in the test methods. Three individual test specimens were tested for tensile strength, and two each for tear resistance and puncture resistance. The physical properties of the unexposed lining materials that were immersed are presented in Appendix A. A summary of the results of the immersion test is presented in Appendix H.

The range of values for a selection of properties measured on all the samples from each of the eleven polymer types are shown for eight, nineteen, and thirty-one months immersion in Table 23. In all cases, the liners absorbed leachate, but the data show that swelling varies both among types of polymers and within a generic polymer type. The variations within a polymer type result from compounding differences. In some cases, the absorption appeared to have dropped due to changes in the composition of either the leachate or the liner due to plasticizer loss.

Table 23 also shows the range of values for the retention of tensile strength and elongation, and changes in hardness. Again, within a group of lining materials of a given generic polymer type there are variations due to compound differences. The range shown for a single material shows the effect of grain direction on properties.

The effect of immersion in leachate up to 31 months appears to have a relatively mild effect upon most of the membranes as shown for tensile strength retention versus immersion (Figure 16). Of the 28 sheetings in the exposure test, 11 increased in tensile, 10 decreased, and 7 remained essentially unchanged. The maximum average retention after 31 months of exposure was 135% and the lowest was 70%. The effect of immersion on the modulus (i.e., stress at 200% elongation) of the same materials is shown in Table 24. The PVC membranes had a small spread in values and retained their original tensile strength as well as modulus. Overall, the polyolefins, such as polyethylene, polybutylene, and elasticized polyolefin, exhibited the lowest swelling and highest retention values.

Tear resistance of the polymeric membranes sustained the greatest variation in retention of properties on exposure to the MSW leachate. Retention values of tear strength averaged for the two test directions ranged from 54%

TABLE 23. SUMMARY OF THE EFFECTS OF IMMERSION ON POLYMERIC MEMBRANE LINERS IN LEACHATE FOR 8, 19, and 31 MONTHS[a]

Polymer type	Number of liners in tests	Weight increase, %			Tensile strength, % original			Elongation, % original			Change in hardness, Duro A, points		
		8 mo.	19 mo.	31 mo[b]	8 mo.	19 mo.	31 mo.	8 mo.	19 mo.	31 mo.	8 mo.	19 mo.	31 mo.
Butyl rubber	1	1.8	3.5	25	90-97	89-94	92	104-106	99	90-92	0	0	-1
Chlorinated polyethylene	3	8-10	16-18	25-28	80-115	81-106	78-106	64-135	76-108	71-103	-5 to 1	-8 to -2	-11 to -1
Chlorosulfonated polyethylene	3	13-19	16-27	19-32	82-124	95-132	103-138	97-107	77-94	69-86	-20 to -4	-26 to -5	-21 to -3
Elasticized polyolefin	1	0.1	1.6	8	86-94	96-107	98-106	91-92	102	96-98	0	-2	-1
Ethylene propylene rubber	5	1-21	1-12	8-24	64-107	86-93	94-113	76-138	83-146	88-138	-1 to +2	-2 to -1	-3 to +5
Neoprene	4	1-19	3-32	5-88	69-100[c]	60-102	68-105	82-103[c]	76-104	78-146	-11 to +5	-12 to +3	-18 to +4
Polybutylene	1	0.1	0.8	...	96-99	94-95	84-97	96-97	96	86-89	-3	-5	-3
Polyester elastomer	1	2.0	1.9	16	99-115	52-94	81-90	101-108	92-94	80-96	-4	-6	-3
Low density polyethylene	1	0.6	0.7	3	110-180	92-149	118-161	96-181	67-192	100-168	...	...	...
Polyvinyl chloride	7	1-3	1-6	4-24	91-110	91-111	87-117	98-139	100-129	79-120	-2 to +1	-6 to +1	-6 to +3
Polyvinyl chloride + pitch	1	6	8	14	92	88-93	101-104	109-133	94-117	80-103	-2	+1	+1

[a] Ranges of retention values for tensile strength and elongation are lowest and highest averaged values obtained for either machine or transverse directions of all tensile specimens within the group of slab specimens of a given polymer type.

[b] Some samples were inadequately cleaned, so some values are high.

[c] Data on fabric-reinforced neoprene liner number 42 were not included.

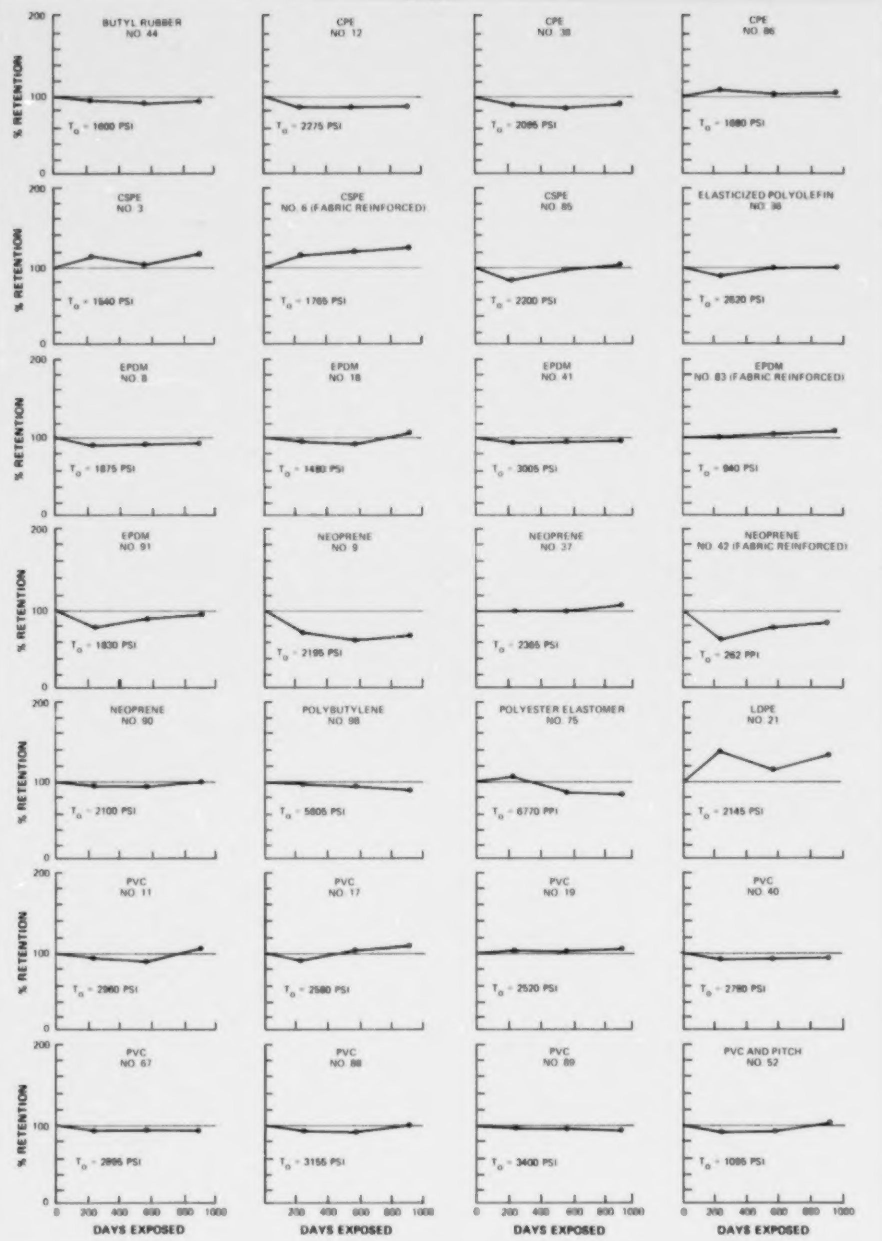

Figure 16. Retention of tensile strength of the individual polymeric membranes as a function of immersion time in landfill leachate. Tensile strength values based upon the average data obtained in the machine and transverse directions. Liner numbers and initial tensile strength for each liner are shown. Data are given for 8, 19, and 31 months.

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TABLE 24. RETENTION OF MODULUS[a] OF POLYMERIC MEMBRANE LINER MATERIALS ON IMMERSION IN LANDFILL LEACHATE

Polymer	Liner no.[b]	Modulus S-200 of unexposed membrane, psi	Retention on exposure of original value, % 8 mo.	19 mo.	31 mo.
Butyl rubber	44	685	86	90	98
Chlorinated polyethylene	12	1330	85	89	95
	38	1205	89	90	104
	86	810	98	106	133
Chlorosulfonated polyethylene	3	735	54	46	57
	6R	1525	116	136	...
	85	1770	77	108	130
Elasticized polyolefin	36	1020	99	103	107
Ethylene propylene rubber	8	655	134	131	134
	18	755	111	109	117
	41	1040	100	99	105
	83R	920	98	98	104
	91	855	91	92	98
Neoprene	9	1235	79	77	76
	37	1635	100	100	99
	90	1340	93	101	115
Polybutylene	98	3120	101	101	106
Polyester elastomer	75	2735	102	98	100
Polyethylene	21	1260	106	102	106
Polyvinyl chloride	11	2125	87	85	98
	17	1965	80	84	94
	19	1740	89	94	112
	40	1720	91	91	104
	67	1705	92	105	117
	88	2400	79	88	101
	89	2455	96	95	105
Polyvinyl chloride + pitch[c]	52	1020	85	86	...

[a] Average of stress at 200% elongation (S-200) measured in machine and transverse directions.

[b] R indicates that the membrane is fabric reinforced.

[c] S-100 values given; original and subsequent exposed specimens failed at less than 200% elongation.

for a CSPE membrane to 145% for the polybutylene film used in making the leachate collection bags. As with leachate absorption and other physical properties, the effects on tear resistance varied with polymer type and within a polymer type, from membrane-to-membrane. For example, in the case of the seven PVC liners, the retention values at 31 months varied from 84% to 116%. As a function of exposure time, the values first dropped and then tended to increase, as was also shown by the modulus values.

WATER ABSORPTION

Since MSW leachate is primarily water which, in itself, can affect the properties of polymeric materials particularly on prolonged exposure, water absorption studies were conducted according to ASTM Test Method D570 (ASTM, 1975). In this test, 1 x 3 inch specimens are immersed in water. The fabric ends of the fabric-reinforced specimens were not sealed. In addition to water absorption, the loss of soluble fraction can be assessed at the end of the exposure. Absorption tests were run at room temperature and at 70°C. The objective of these studies was to determine the correlation of swelling by leachate with that by water. The tests at 70°C were intended as a form of accelerated aging. We proposed to determine whether or not the swelling of the liner materials came to equilibrium on extended immersion times.

The results of the water absorption tests of specimens of 11 polymeric membranes after immersion in water for up to 186 weeks, both at room temperature and at 70°C, are presented in Table 25. The results for the two temperatures generally ordered the same; however, one of the major differences was with one of the PVC liners (No. 11), which yielded the lowest swell at room temperature, but was sixth at 70°C. The liner materials that had the lowest swell were the polyvinyl chloride, the elasticized polyolefin, and the ethylene propylene rubber materials; those that swelled the most were the membranes based on neoprene, CSPE, and CPE. The CPE and the EPDM materials essentially reached equilibrium swell at 70°C in 100 weeks. A PVC liner appeared to have reached equilibrium swell; however, it hardened because of loss of plasticizer. It appeared that at 70°C several of the other liner materials, particularly the neoprene and CSPE, would continue to swell for considerable lengths of time. The large difference in absorption after 186 weeks at 70°C between PVC 11 and PVC 59 illustrates the differences in properties that can occur within a generic group of compounds based upon a single type of polymer.

The results of the water absorption test at 70°C suggest that the test conditions may be too harsh to be of value as an accelerated aging test for polymeric membrane materials for MSW landfill use. A test temperature of 50°C is recommended for future accelerated testing.

SIMULTANEOUS EXPOSURE OF MEMBRANE LINERS TO WATER AND LEACHATE AND TO WATER AND 5% SALT SOLUTION

The pouch test which was developed in this project offers the opportunity of exposure of liner materials to two fluids at the same time. In

TABLE 25. WATER ABSORPTION OF ELEVEN SELECTED MEMBRANE LINER MATERIALS AT ROOM TEMPERATURE AND AT 70°C[a]

		Water absorbed, % by weight											
		At room temperature						At 70°C					
Polymer	Liner number[b]	1 week	11 weeks	44 weeks	100 weeks	159 weeks	186 weeks	1 week	11 weeks	44 weeks	100 weeks	159 weeks	186 weeks
Butyl rubber	57R	0.82	3.22	4.50	6.4	10.92	10.76	4.62	17.54	53.9	103.2	(c)	141.3
Chlorinated polyethylene	77	1.63	5.53	10.2	12.5	16.85	16.51	15.9	58.4	140.0	179.3	178.89	196.14
Chlorosulfonated polyethylene	6R	3.44	6.97	10.9	16.3	20.81	19.42	22.1	131.0	245.6	370.5	438.16	471.40
Elasticized polyolefin	36	0.39	0.52	0.0	4.5	0.93	0.38	0.36	0.45	0.57	8.7	-4.19	-8.48
Ethylene propylene rubber	8	0.50	1.30	1.56	2.25	3.48	3.53	1.11	3.55	10.8	17.8	18.96[d]	18.53
	26	1.20	1.84	1.49	2.56	3.85	3.61	1.44	4.52	11.20	17.4	21.08	22.60
Neoprene	43R	3.80	13.62	37.8	75.1	67.20	63.11	14.1	107.0	240.0	(e)	(e)	(e)
	82	2.43	8.29	18.5	32.1	44.00	52.48	8.11	47.4	191.4	295.0	349.95	(e)
Polyester elastomer	75	1.07	1.05	0.67	1.31	1.61	0.36	1.28	1.10	0.72	0.22	0.79	(e)
Polyvinyl chloride	11	1.29	1.10	0.70	1.25	1.74	-0.21	5.59	12.13	39.2	87.4	126.31	164.28
	59	1.59	2.34	2.43	2.98	4.53	1.55	4.87	8.25	24.0	25.5[f]	26.17	26.86

[a] ASTM D570-63 specimens 1 x 3 inches in deionized water.

[b] R indicates that liner was fabric reinforced.

[c] Specimen not weighed.

[d] One-hundred sixty-eight weeks of exposure.

[e] Specimens disintegrated.

[f] Specimens have become hard, indicating loss of plasticizer.

this test, a small pouch is made of the membrane liner and filled with a test fluid, such as leachate, and the filled pouch placed in a deionized water solution in a polybutylene bag. The test was basically designed for testing the permeability of materials in a condition which simulates a liner in a landfill in which one side of the liner would be in contact with leachate and the other side in contact with groundwater.

In this project pouches containing two fluids were tested: (1) MSW leachate which was generated in the simulators, and (2) 5% sodium chloride solution (NaCl). The latter solution, being of known composition, was used to measure the movement of ions and to set up a known concentration differential across the membrane.

After the test had been run and measurements made for permeability purposes, the pouches were emptied and the properties of the membranes measured. The retention of the physical properties, with respect to the original properties of the materials, are shown in Tables 26 and 27. The exposure periods ranged from 310 days to 1220 days. Only materials that could be heat seamed or solvent welded were included in the pouch test. Vulcanized rubber sheetings require wide seams and vulcanized adhesives which require modification of the pouch design. In determining the properties, the following measurements were made:

1. Volatiles of the membrane to determine the amount of liquid that was absorbed.

2. Extractables of the membrane after drying to remove the volatiles. By this test, the amount of plasticizer that may have been lost during the exposure period can be determined by comparing the extractables after exposure with that of the unexposed sheeting.

3. The tensile properties in the machine and transverse directions, ASTM D412.

4. Tear strength in machine and transverse directions, ASTM D624 (Die C).

5. Puncture resistance, Federal Test Method Standard 101B, Method 2065.

6. Hardness, ASTM D2240.

In the case of the pouches containing leachate, the polyester film exposed for 1220 days showed the lowest retention of properties. This behavior is indicative of a degradation of the polymer, as the volatiles content and difference in extractables are quite low. The CPE and CSPE sheetings showed significant changes in properties. The CPE membranes which swelled the most during the test also showed a significant decrease in tensile strength. The CSPE sheetings appeared to have crosslinked during the exposure period; they increased in tensile strength and modulus, but decreased in elongation and in tear strength. The effects of the exposure on the PVC materials varied and each PVC membrane probably lost some of its original

TABLE 26. RETENTION OF PHYSICAL PROPERTIES OF POLYMERIC MEMBRANE LINING MATERIALS AFTER EXPOSURE IN POUCH TEST TO MSW LEACHATE

Polymer		CPE		CSPE	ELPO	Polybutylene	Polyester	Polyethylene	PVC				
Liner number		77	86	55	36	98	75	21	11	17	19	59	93
Nominal thickness, mils		29	22	35	23	7.5	7	11	30	20	22	33	11
Type of compound		TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP
Exposure time, days		1220	340	325	1220	340	1220	340	1220	1220	340	1220	340
	Direction of test												
Volatiles of exposed liner, %		13.67	0.18	0.12	0.45	0.03	1.07	0.09	2.39	3.99	0.83	2.50	0.03
Extractables, %		9.82	12.91	2.57	5.68	3.40	3.05	3.85	32.45	34.38	37.63	33.75	30.61
Tensile strength of polymer, % retention	Machine	101	83	137	106	91	74	186	106	99	103	104	107
	Transverse	76	79	138	98	89	73	109	101	98	115	102	82
Elongation at break, % retention	Machine	92	89	83	100	96	89	156	103	117	109	97	81
	Transverse	78	76	83	100	96	84	98	97	124	122	100	97
Set after break, % retention	Machine	110	48	75	107	68	99	212	103	76	69	109	73
	Transverse	69	37	74	106	63	84	79	82	90	100	108	128
S-100, % retention	Machine	93	89	114	110	98	92	128	118	102	125	105	133
	Transverse	90	102	127	101	99	103	114	123	100	114	106	98
S-200, % retention	Machine	101	91	133	112	97	89	122	108	88	109	104	126
	Transverse	108	111	149	104	96	103	110	112	86	104	102	88
Tear strength, % retention	Machine	70	72	68	100	142	75	118	94	84	103	96	104
	Transverse	66	65	70	105	118	75	99	97	88	109	92	100
Puncture resistance													
Stress, % retention		96	110	101	120	101	62	101	120	128	142	109	119
Elongation, % retention		102	121	67	108	82	72	145	111	136	127	95	135
Change in hardness, Durometer pts.		-4A	-9A	-1A	-4A	-10A	-2A	-12A	-3A	-6A	0	+4A	0

TABLE 27. RETENTION OF PHYSICAL PROPERTIES OF POLYMERIC MEMBRANE LINING MATERIALS AFTER EXPOSURE IN POUCH TEST TO 5% NaCl SOLUTION

Polymer		CPE	CSPE		ELPO	Polybutylene	Polyester	Polyethylene	PVC			
Liner number[a]		86	6R	55	36	98	75	21	11	17	19	59
Nominal thickness, mils		22	32	35	23	7.5	7	11	30	20	22	33
Type of compound		TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP
Exposure time, days		316	1151	315	1151	316	981[b]	310	750[b]	310	315	1152
	Direction of test											
Volatiles of exposed liner, %		5.97	8.71	7.59	0.38	0.24	...	-0.40	...	0.42	0.52	0.90
Extractables, %		14.00	3.74	3.38	5.23	3.72	...	3.98	...	33.12	37.85	35.53
Tensile strength of fabric, % retention	Machine	...	99	...	...	...	...	...	...	...	...	...
	Transverse	...	76	...	...	...	...	...	...	...	...	...
Tensile strength of compound, % retention	Machine	100	132	144	93	101	81	171	101	103	106	106
	Transverse	105	127	141	109	103	88	110	103	96	114	105
Elongation at break, % retention	Machine	99	94	87	96	99	89	152	112	126	115	92
	Transverse	68	96	80	105	96	83	98	115	119	121	96
Set after break, % retention	Machine	48	83	73	98	67	91	201	108	84	77	107
	Transverse	34	90	67	113	62	82	80	110	81	94	102
S-100, % retention	Machine	99	106	124	116	110	109	123	103	99	122	119
	Transverse	133	106	136	121	115	114	118	106	97	117	121
S-200, % retention	Machine	101	128	144	110	105	107	114	97	88	104	114
	Transverse	152	131	161	117	109	119	115	96	86	103	114
Tear strength, % retention	Machine	88	83	80	105	131	100	88	...	88	86	100
	Transverse	93	76	77	110	118	103	126	...	93	107	91
Puncture resistance												
Stress, % retention		95	126	120	115	104	75	107	...	127	125	131
Elongation, % retention		105	95	89	113	85	85	84	...	136	113	108
Change in hardness, Durometer points 10 second reading		-7A	-6A	+5A	-2A	-3A	-1A	-9A	+4A	-4A	+2A	+4A

[a] R indicates liner was fabric reinforced.

[b] Pouch failed at seam.

plasticizer. The olefinic partially crystalline materials, such as polyethylene and elastiziced polyolefin, showed little change in properties.

The pouches filled with the 5% salt solution were much less affected by the exposure and, in several cases, there were actual improvements in physical properties during exposure.

Overall, the effects of the leachate and of the salt solution on these liners, except for the polyester pouch filled with leachate, was negligible and indicated that considerably longer exposure periods could be sustained without substantial loss of properties.

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SECTION 10

PERMEABILITY OF POLYMERIC MEMBRANE LINERS

The low permeabilities of polymer membrane liners, compared with those of soils and most admix liner materials, have made it difficult to obtain compatible permeability data for all these materials. Polymeric membrane liners are essentially nonporous. The rate of transmission of a liquid, such as water, through a polymeric membrane, depends upon the solubility of the liquid in the liner and the rate of diffusion of the molecules of the liquid through the liner. Because of this, permeameters normally used for soils are not applicable for measuring the permeability of membranes. Consequently, the polymeric membrane liner industry has been using water vapor transmission as a measure of the permeability of polymeric liners. This type of test was used to determine the permeability of most of the polymeric membranes that were investigated in this project.

WATER VAPOR PERMEABILITY

The test method used in our initial measurements basically followed ASTM E 96, "Water Vapor Transmission of Materials in Sheet Form - Method BW". In this test, a cup with a membrane specimen cover is inverted to wet the specimen. The cup, in the inverted position, is placed in a box having controlled temperature, humidity, and air stream, and its loss in weight is observed as a function of time. This test is intended for those applications in which one side is wetted under conditions where the hydraulic head is relatively unimportant and the moisture transfer is governed by capillary and water vapor diffusion forces. The driving force is supplied by the difference in the relative humidity on the two sides of the membrane.

The conditions under which the tests were initially performed varied somewhat from those specified in the ASTM Test Method E 96, leading to high absolute values of vapor transmission and permeability. In particular, the relative humidity on the outside of the cups was significantly less than 50% and the air velocity was substantially higher than that called for in the method.

To comply with the test conditions of the ASTM method, we constructed a small cabinet to hold the cups. The cabinet has a built-in controlled air flow and is operated in a constant-temperature and humidity room controlled at 72±1°F and 50±2% relative humidity. The effect of the change in test conditions on the water vapor transmission values is shown in Table 28. The values for water vapor transmission and permeability are significantly lower when the tests are run under the ASTM conditions, rather than under the conditions existing in the first tests. This probably reflects the higher

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TABLE 28. EFFECTS OF TEST CONDITIONS ON WATER VAPOR PERMEABILITY OF POLYMERIC MEMBRANES

	Liner number	Thickness		Water vapor permeability, cm·g/d·m^2·mmHg (metric perm-cm)x10^3 Test conditions	
		mils	cm	ASTM E96	Initial test[a]
Chlorinated polyethylene	12	33.3	0.085	1.76	3.70
Chlorosulfonated polyethylene	6R	37.0	0.094	3.79	5.70
Polyvinyl chloride	17	20.0	0.051	12.0	15.0

[a] Results of tests made in lower relative humidity and higher air flow than specified in ASTM E96. The temperatures ranged from 68-78°F and the relative humidity ranged from 26 to 47% in the time interval that the test was run.

relative humidity and lower air velocity of the ASTM conditions. The driving force for transmission increases with the magnitude of the difference in humidity on the two sides of the membrane.

The water vapor permeability of 27 polymeric membrane liners, including three previously tested, was then determined. The results are presented in Table 29.

The polyester liner, with a thickness of eight mils, is the thinnest membrane in the series and has the highest rate of water vapor transmission. However, its water vapor permeability, which corrects for thickness and is a property of the liner, is in the same range as that of polyvinyl chloride compositions, some of which are considerably more permeable than others. There is a threefold variation from the lowest permeability to the highest in the case of polyvinyl chloride liners. As a group, the polyvinyl chloride liners are the most permeable.

The most impermeable materials in this test series are elasticized polyolefin and butyl rubber, both of which have less than one-tenth of the water vapor permeability of polyvinyl chloride. The considerable spread in the values for butyl rubber (Table 29) indicate compound differences. The other liner materials are intermediate in water vapor permeability, with a possible twofold variation among them.

Swelling of polymeric compositions, such as that anticipated for polymeric liners exposed to leachate for long periods, generally increases permeability. Consequently, running the permeability tests for long periods should result in some swelling of the test specimens and higher permeability. Table 30 presents such results for 11 liner specimens. Permeability values obtained from the 35th to 63rd day are compared with those obtained before the

TABLE 29. WATER VAPOR PERMEABILITY OF POLYMERIC MEMBRANE LINERS, ASTM E96, METHOD BW[a]

Polymer	Liner number	Thickness		Test time, days	Rate of water vapor transmission, g/d·m2	Water vapor permeance, $g/d \cdot m^2 \cdot mmHg$ (metric perm)x10^2	Water vapor permeability, $cm \cdot g/d \cdot m^2 \cdot mmHg$ (metric perm-cm)x10^3)
		mils	cm				
Butyl rubber	22	73.3	0.185	49	0.097	0.75	1.39
	57	33.5	0.085	21	0.020	0.17	0.15
Chlorinated polyethylene	12	33.3	0.085	28	0.264	2.10	1.76
	38	32.3	0.082	21	0.361	2.90	2.35
	77	31.0	0.079	21	0.320	2.80	2.10
	86	21.0	0.053	28	0.643	5.10	2.72
Chlorosulfonated polyethylene	3	31.0	0.079	32	0.634	5.00	3.97
	6R[b]	37.0	0.094	40	0.422	4.21	3.79
	55	35.0	0.089	42	0.438	3.47	3.09
Elasticized polyolefin	36	28.3	0.072	28	0.142	1.20	0.85
Ethylene propylene rubber	8	67.0	0.170	28	0.172	1.40	2.52
	18	48.5	0.123	28	0.314	2.49	3.07
	26	38.0	0.097	28	0.327	2.80	2.72
	41	20.0	0.051	21	0.270	2.15	1.09
	83R[b]	37.0	0.094	28	0.190	1.50	1.42
Neoprene	9	61.0	0.159	21	0.237	1.90	2.89
	42R[b]	20.0	0.051	42	0.304	24.1	1.22
	43	31.5	0.080	28	0.448	3.90	3.12
	82	61.2	0.155	63	0.240	2.00	3.11
Polyester elastomer	75	8.0	0.020	21	10.50	91.0	18.2
Polyvinyl chloride	11	30.0	0.076	28	1.85	16.0	12.2
	17	20.0	0.051	35	2.97	24.0	12.0
	19	21.0	0.054	42	2.78	22.0	11.8
	40	32.5	0.083	42	4.17	33.0	27.3
	59	33.0	0.084	21	4.20	36.0	30.2
	88	20.5	0.052	35	2.94	23.0	12.1
	89	11.0	0.028	35	4.42	35.0	9.77

[a] Average temperature, 22°C; average relative humidity, 42%.

[b] Fabric-reinforced.

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TABLE 30. EFFECT OF TEST TIME ON WATER VAPOR PERMEABILITY OF MEMBRANES IN E 96 BW TEST

Polymer	Liner number	Permeability metric perm·cm x 10^3 7-28 days[a]	Permeability metric perm·cm x 10^3 35-63 days[b]	Increase, %
Butyl rubber	57	0.18	0.22	22
Chlorinated polyethylene	77	2.63	2.87	9
Chlorosulfonated polyethylene	6R[c]	2.07	2.57	24
Elasticized polyolefin	36	1.09	1.18	8
Ethylene propylene rubber	8	2.87	3.11	8
	26	3.40	3.68	8
Neoprene	43	3.90	5.14	32
	82	1.61	3.85	139
Polyester elastomer	75	1.14	1.18	3
Polyvinyl chloride	11	15.25	17.09	12
	59	38.21	40.98	7

[a] Temperature, 22.2°C; relative humidity, 54%, ΔP, 9.23 mm Hg.

[b] Temperature, 23.3°C; relative humidity, 55%, ΔP, 9.65 mm Hg.

[c] Fabric reinforced.

35th day. In all cases, values determined in the 35th to 63rd day interval are higher than those that were determined in the 7-to 28-day interval. Furthermore, the increases tend to follow the respective tendencies of the liner specimens to swell in water.

POUCH TEST FOR ASSESSING MEMBRANE LINER MATERIALS

As the permeability of membrane liners to water and to other leachate components under landfill conditions may not necessarily be reflected by the water vapor permeability as determined by ASTM E96, other methods of measuring the permeability of liner materials, therefore, were investigated. Of these, the most promising is the "pouch test", in which leachate is sealed into pouches fabricated from the liner membranes under test. These pouches are then placed in a bag containing deionized water. Such a condition simulates a pond containing a waste. The permeation of dissolved leachate components into the deionized water is followed by pH and electrical conductivity measurements and permeation of water into the pouch by changes in weight of the pouch containing the leachate.

To demonstrate the feasibility of the test procedure, initial experiments were carried out on two sets of pouches fabricated from heat-sealable liner materials. One set was filled with leachate and the second set with a 5% aqueous solution of sodium chloride. The liner materials in these tests include the following polymers:

- Chlorinated polyethylene.
- Chlorosulfonated polyethylene.
- Elasticized polyolefin.
- Polyester elastomer.
- Polyinyl chloride (three different membranes).

Figure 17 is a schematic of the pouch assembly. The individual pouches for the leachate were 20 x 14 cm, which gave an exposable surface of approximately 560 cm^2. For the sodium chloride solution, the pouches were 17x12 cm, which yielded an exposable surface of approximately 400 cm^2.

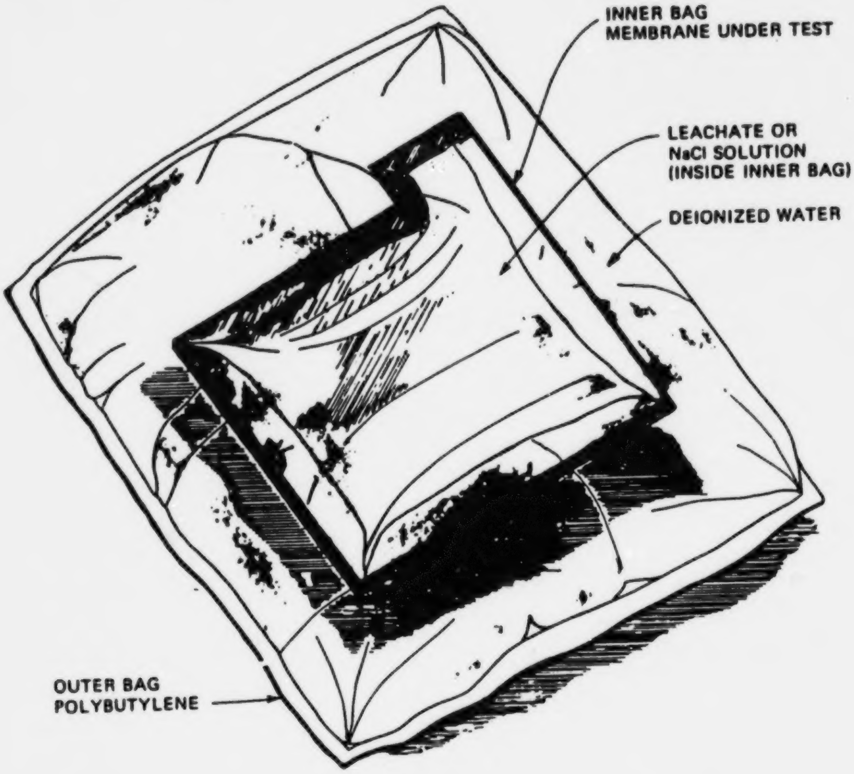
INNER BAG
MEMBRANE UNDER TEST
LEACHATE OR
NaCl SOLUTION
(INSIDE INNER BAG)
DEIONIZED WATER
OUTER BAG
POLYBUTYLENE

Figure 17. Schematic of pouch assembly, showing inner bag made of membrane material under test. The inner bag is filled with leachate or 5% salt solution and sealed at the neck. The outer polybutylene bag, which can be easily opened, is filled with deionized water. The water in the outer bag is monitored for pH and conductivity; the inner bag is monitored for weight change.

Each pouch was constructed with a neck through which a test liquid could be introduced. After the pouch was filled, the neck was heat sealed. Either 100 mL of leachate (composition shown in Table 31) or 305-490 mL of 5% salt solution were added to the pouches.

The following tests were performed during the exposure of these pouches:

1. In the case of the inner pouches containing leachate, the deionized water was tested periodically for pH, conductivity, and for the odor of butyric acid.

2. The pouches containing the test liquid were removed periodically from the water and weighed.

TABLE 31. CHARACTERISTICS OF LEACHATE IN POUCHES[a]

Property	Value
Total solids, %	2.0[b]
Total volatile solids, %	1.1[b]
Chemical oxygen demand, g/L	35.7[b]
Total volatile acids, g/L	15.2[b]
pH	5.15[b]
Conductivity, µmho	11,500

[a] Amount of leachate in each bag is 100 mL. Samples were taken from the blend of leachates collected on November 8, 1976.

[b] Average value for the leachates taken from 12 simulators.

Results of the tests after extended exposures are given in Tables 32 through 35.

In the case of pouches containing leachate, after 500 days of exposure it was apparent that there was movement through the liner by both the water and the dissolved ingredients of the leachate (Table 32). An increase in electrical conductivity occurred, indicating the permeation of some ions from the leachate into the deionized water. Also, there was an increase in the weight of the pouches containing leachate. In this series, the elasticized polyolefin yielded the lowest transmission of water and dissolved components, and the chlorinated polyethylene appeared to be the most permeable. The order of liner materials for increasing conductivity of the deionized water and for the increase in the weight of the pouches containing leachate is presented in Table 33.

TABLE 32. TESTS OF MEMBRANE LINER POUCHES[a] FILLED WITH LEACHATE
Transmission of Water and Ions Through Pouch Walls Due to Osmosis

		Original values			Values at 70 days			Values at 500 days		
	Liner number	pH[b]	Conductivity[b], μmho	Weight of filled bag, g	pH[b]	Conductivity[b], μmho	Weight increase[c], g	pH[b]	Conductivity[b], μmho	Weight increase[c], g
Chlorinated polyethylene	77	5.7	5.2	170.91	5.8	29.7	1.68	6.5	124.0	4.74
Elasticized polyolefin	36	5.1	4.3	142.63	5.0	9.82	-0.07	4.5	17.8	0.22
Polyester elastomer	75	4.0	20.5	112.25	3.5	73.0	0.58	6.4	50.0	2.95
Polyvinyl chloride	11	5.8	6.0	166.88	4.4	30.9	0.41	6.0	32.0	1.12
Polyvinyl chloride	17	5.0	13.3	138.28	2.9	310.1	0.33	2.8	325.0	1.37
Polyvinyl chloride	59	5.7	5.9	170.14	3.8	61.5	0.97	6.3	23.2	1.21
Blank	...	5.5	1.33	...	5.7	1.75	...	4.3	11.6	...

[a] Area of each bag exposed to test fluid is 560 cm^2.

[b] pH and conductivity of deionized water outside the pouches containing leachate.

[c] Weight increase of pouches containing leachate.

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TABLE 33. TESTS OF POUCHES CONTAINING LEACHATE - ORDER OF LINERS BY INCREASING BAG WEIGHT AND BY CONDUCTIVITY OF DEIONIZED WATER

Order of increase	Conductivity of deionized water	Weight of bag
1	Elasticized polyolefin (#36)	Elasticized polyolefin (#36)
2	Polyvinyl chloride (#59)	Polyvinyl chloride (#11)
3	Polyvinyl chloride (#11)	Polyvinyl chloride (#59)
4	Polyester elastomer (#75)	Polyvinyl chloride (#17)
5	Chlorinated polyethylene (#77)	Polyester elastomer (#75)
6	Polyvinyl chloride (#17)	Chlorinated polyethylene (#77)

Somewhat similar results were obtained when the inner pouches were filled with 5% sodium chloride solution (Table 34). Again, the elasticized polyolefin was the least permeable of the liners and one of the polyvinyl chloride membranes (#11) was the second least permeable. The order for the liners in this set is shown in Table 35 for increasing conductivity of the deionized water and increasing weight in the pouches.

After the completion of individual tests, the pouches were cut apart and physical properties of the liner materials were measured. Results are reported in Section 9.

Overall, the pouch test appears to be a useful laboratory test for assessing membrane liner materials, both from the standpoint of permeability to water and to dissolved constituents in the waste. Because of the difficulty in making tight, durable seams, the procedure has been only applicable to thermoplastic materials which can be either heat sealed or seamed with bodied solvents. Good seams for preparing pouches of vulcanized sheeting must be developed. Leaks in a seam quickly become apparent because of a drastic change in the slope of the conductivity measurements with time. Pouch tests should be run in duplicate to assure valid results.

TOP PRESSURE PERMEAMETER

In order to assess the permeability of polymeric membrane liner materials to selected liquids under a modest hydraulic head, a pressurized liquid permeameter was designed and constructed for this project to measure the flow through thin polymeric membranes of water or aqueous solutions. The permeameter was constructed of stainless steel and was designed to measure permeabilities less than 10^{-10} cm sec^{-1}. The specimen surface exposed to test liquid was 730 cm^2. Thus, this permeameter provided increased sensitivity and less distortion than other smaller available devices due to the use of lower pressures, larger surface areas, and finer capillaries to measure the permeated fluid.

TABLE 34. TESTS OF MEMBRANE LINER POUCHES[a] FILLED WITH 5% NaCl SOLUTION - TRANSMISSION OF WATER AND IONS THROUGH POUCH WALLS DUE TO OSMOSIS

	Liner number	Original values		Values at 113 days		Values at 200 days	
		Conductivity[b], µmho	Weight of filled bag, g	Conductivity[b], µmho	Weight increase[c], g	Conductivity[b], µmho	Weight increase[c], g
Chlorinated polyethylene	77	1.92	370.91	23.3	1.01	31.2	+1.56
Chlorosulfonated polyethylene	6R	3.48	391.02	86.0	1.36	113.0	+2.20
Elasticized polyolefin	36	1.51	329.50	9.5	-0.02	10.9	+0.06
Polyester elastomer	75	1.62	424.35	22.9	2.61	30.0	+5.30
Polyvinyl chloride	11	1.67	479.81	13.7	0.26	15.3	+0.69
Polyvinyl chloride	59	1.77	537.80	19.5	1.07	21.5	+1.86
Blank (polybutylene bag)	...	0.63	...	7.8	...	6.6	...

[a] Area of pouch exposed to test fluid was 480 cm^2

[b] Conductivity of deionized water outside the test pouches.

[c] Weight increase of pouches.

TABLE 35. TESTS OF POUCHES CONTAINING 5% SALT SOLUTION - ORDER OF LINERS BY INCREASING BAG WEIGHT AND BY CONDUCTIVITY OF DEIONIZED WATER

Order of increase	Conductivity of deionized water	Weight of bag
1	Elasticized polyolefin (#36)	Elasticized polyolefin (#36)
2	Polyvinyl chloride (#11)	Polyvinyl chloride (#11)
3	Polyvinyl chloride (#59)	Chlorinated polyethylene (#77)
4	Polyester elastomer (#75)	Polyvinyl chloride (#59)
5	Chlorinated polyethylene (#77)	Chlorosulfonated polyethylene (#6)
6	Chlorosulfonated polyethylene (#6)	Polyester elastomer (#75)

Unfortunately, some design and equipment inadequacies precluded successful testing and reporting at the extremely low permeabilities of polymeric membranes. The support screen placed in the cavity of the downstream plate was not of a fine enough mesh and allowed distortions in the membrane surface. Operation of the top pressure permeameter resulted in creep of the specimen, which could not be quantitatively accounted for in a satisfactory manner. The placement of the O-ring between the membrane and the downstream plate contributed to the problem of creep of the liner specimen. Placing the O-ring seal on the upstream side would have been a better design.

PERMEABILITY OF POLYMERIC MEMBRANE LINER MATERIALS TO GASES

In addition to leachate, municipal solid waste in its decomposition generates gases, particularly methane and carbon dioxide which are pollutants and need to be controlled. Polymeric membranes are often used as gas barriers and can be effective in controlling methane and carbon dioxide. However, gas permeability or, more importantly, gas transmission rates, for membrane liners depend on such factors as:

- Polymer type.
- Composition of compound.
- Thickness of membrane.
- Temperature.
- Pressure differential.
- Type of gas.

Most data in the literature on the permeability of polymers are for simple compounds, that is, compounds that contain essentially the polymer only. Also, the amount of data on methane is limited. Consequently, a study was undertaken to measure the permeability of commercial polymer membranes to methane and to CO_2.

Eight different liner materials were tested at various temperatures and pressures. Although all measurements were obtained with single, pure gases,

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the equipment can also be used to study the effects of exposure to gas mixtures.

The measurements were made in accordance with the volumetric method of ASTM D1434, using Custom Scientific Instrument's permeameter, Model CS-135. In this test, the specimen is mounted between two plates and saturated from both sides with gas. Temperature control of cell and gas temperature is maintained with a water bath and circulator. One side of the membrane is pressurized with the gas, while the other side is filled with the same gas at atmospheric pressure. The permeating gas causes a slug of methyl isobutyl ketone to rise in a capillary tube fitted to the unpressurized side; the slug serves as a flow indicator and as a seal to prevent the intrusion of room air into the cell. Temperature, pressure, and capillary size may be adjusted to facilitate accurate measurements or to study diffusion under specified conditions.

Gas transmission rates (GTR) of several polymeric liners of different polymer compositions and thicknesses were measured. Temperature was varied from 10°C to 30°C and pressure was varied up to 3 atmospheres. The values measured are presented in Table 36, along with data from other sources on liner materials and on polymers used in liner compounds. Low permeability of the polybutylene to methane at 10°C is of particular interest. This material was used to fabricate the gas collection bags attached to the covers of the sealed leachate generators. Tests of silicone rubber were included as part of this study, because of the high gas permeability of this rubber and because we had used it in the water permeability testing. The transmission rate of methane through silicone is more than two orders of magnitude above those of other rubber membranes and is similar to differences measured in the moisture vapor permeability test (ASTM E-96). Although a definite correlation was not established, the transmission through a membrane in one test system may, within limits, be approximated from flow data obtained under other conditions.

The data in Table 36 confirm the variation in gas transmission rates arising from the factors listed above. In particular, they show the high transmission rates of CO_2 compared with those of the methane and the significance of thickness, temperature, and polymer type on gas transmission rates. CPE, CSPE, and butyl rubber membranes appear to have lowest methane transmission.

TABLE 36. GAS TRANSMISSION RATES[a] OF POLYMERS AND COMMERCIAL MEMBRANES

Material	Thickness mils	Temperature, °C	GTR, mL/m^2-d-1 atm				
			CH_4	CO_2	H_2	O_2	N_2
Butyl rubber[b]	30	?	56	541	548	44	7
Neoprene W[b]	30	?	222	2197	2002	387	100
Chlorosulfonated polyethylene[c]	36	23±2	91	...	...	...	...
Chlorosulfonated polyethylene membrane[b]	30	?	142	1560	1092	208	88
Polyvinyl chloride membrane[c]	10	23±2	1760	...	...	...	...
	30	23±2	766	...	...	...	...
	30	23±2	150	...	...	...	...
Chlorinated polyethylene membrane[c]	30	23±2	30	...	...	...	...
Polyvinyl chloride membrane (#93)	10	10	330	2780	...	...	...
	10	30	1150	7730	...	...	...
Silicone rubber	20	10	77,400	...	...	...	...
	20	30	99,500	...	...	...	...
Polyvinyl chloride membrane (#59)	32	10	...	860	...	...	...
	32	30	285	2840	...	...	...
Polybutylene film	4	10	540	...	...	...	...
Low-density polyethylene film (#21)	10	10	370	2450	...	...	...
	10	30	1340	6180	...	...	...
High-density polyethylene sheet	20	23	250	1000	...	...	...
EPDM (thermoplastic) (#83R)	35	10	...	1060	...	...	...
	35	30	...	2720	...	...	...
EPDM (vulcanized) (#8)	60	20	470	...	...	...	...
	60	30	760	...	...	...	...

[a] Gas transmission rates (GTR) = mL of gas permeating per square meter per day at differential pressure of one atmosphere - determined in this project, except as noted.

[b] DuPont permeability coefficient data converted to gas transmission rates. Composition and temperature not reported.

[c] Data from Pantasote.

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SECTION 11

SEAMING OF POLYMERIC LINER SPECIMENS AND EXPOSURE TESTING OF SEAMS

INTRODUCTION

Critical to the effective performance of polymeric membrane liners of impoundments and solid waste landfills is the construction of continuous watertight barriers of approximately uniform strength. At the time this project was initiated (and at present in the case of most polymeric membrane liners), sheetings were manufactured in relatively narrow widths that were seamed together in the factory to make large panels. These panels in turn were assembled at the disposal or impoundment site to make large, continuous sheets which can range up to many acres in area. Therefore, in a liner installed in this manner there are both factory and field seams. In the favorable factory environment, durable seams can be made by a variety of methods depending on the type of polymer. Seaming in the field can pose difficulties, largely due to variability in the ambient conditions. Since this project was begun, several lining materials made in wider sheetings have been introduced, i.e., in widths ranging from 21 to 33 feet; these materials are brought to the site in large rolls and seamed in the field, thus eliminating factory seaming. The seaming of lining materials of this type is not discussed in this report.

In order to function as a liner, a sheeting must have a bonding system which can be used to fulfill the following requirements:

1. The bond between the sheets or panels must be continuous for the length of the seam.
2. The bond between the sheets must approximate the strength of the sheeting and must maintain its strength throughout the service life of the sheeting.
3. The bond must be capable of being formed in the field.

According to the available information, seams appeared to be the most likely source of liner problems and failure. We, therefore, incorporated seams in as many exposure test specimens as possible. In all the polymeric primary test specimens we tested either factory seams or seams made in accordance with the manufacturer's recommended practice. In most cases, adhesives supplied by the manufacturers were used. Test joints were also incorporated in the strips buried in the sand above the primary test specimens in the MSW simulators in an effort to increase the number of bonding systems that were not necessarily recommended by the manufacturers of the specific materials, but which had been recommended by manufacturers of other lining materials based on the same polymer.

BONDING SYSTEMS FOR THE POLYMERIC LINER SPECIMENS

A variety of bonding systems are used in the seaming of polymeric membranes. Selection of the optimum system will depend on the specific liner material. Certain techniques or seaming systems are incompatible with certain liner materials. For instance, dielectric seaming cannot be used to seam a butyl material. In addition, some adhesives are designed for use with a specific sheeting and should not be used with other lining materials even though the two materials may be based on the same polymer. Manufacturers may recommend a specific seaming technique, a specific type of adhesive, or a variety of techniques or adhesives. For instance, the manufacturers of the CPE sheeting used as a primary test specimen recommended three types of bonding systems and specific systems within each type.

The following is a list of seaming techniques that were considered for exposure testing in this project:

- Solvent "welding".
- Bodied solvents.
- Solvent cements.
- Contact cements.
- Vulcanizing adhesives.
- Tapes.
- Thermal (heat) techniques.

Table 37 presents a list of the possible alternatives for seaming polymeric materials depending upon the polymer, type of compound, and location of seaming, i.e., factory or field. Also indicated on the table are the systems included in the exposure tests.

Solvent "Welding"

Solvent "welding" can be achieved by coating the mating surfaces of the sheetings with a suitable solvent for the sheeting material and then pressing the two surfaces together firmly by wiping or rolling. The solvent, which solubilizes the surface of the sheeting and imparts some tack, can be applied either by a brush or with a squeeze bottle. Initial set-up time ranges from five minutes to an hour, depending on the type of material and environmental conditions. A few days are usually needed before the solvent evaporates completely from the joint and the seams achieve full strength. Because the technique requires a solvent which can dissolve the lining material itself, and because crosslinked polymers swell but do not dissolve, this technique can be used only with thermoplastic materials. The CPE primary test specimen was seamed using a 50 part toluene to 50 part tetrahydrofuran mixture. Some CPE and PVC buried specimens were also seamed using solvents. Though this method can be used both in the field and in the factory, it is sensitive to the weather conditions in which it is used, e.g., temperature,

TABLE 37. POSSIBLE BONDING SYSTEMS AVAILABLE IN 1973 FOR SEAMING POLYMERIC MEMBRANE LINERS IN FACTORY AND FIELD, AND SYSTEMS EXPOSED IN THE STUDY

	Type of compound[a]	Place used	Solvents	Bodied solvents	Solvent cements	Contact cements	Vulcanizing adhesives	Tapes	Heat sealed	Dielectric
Butyl rubber	XL	Factory	...	...	...	X	X	...	...	...
		Field	...	...	...	X	X	X	...	...
		Systems in study[b]	...	...	...	...	Ex	...	...	...
Chlorinated polyethylene	TP	Factory	X	X	X	X	...	...	X	X
		Field	X	X	X	X	...	X	X	...
		Systems in study[b]	Ex	Ex	Ex	...	...	...	Ex	...
Chlorosulfonated polyethylene	TP	Factory	X	X	X	X	...	...	X	X
		Field	X	X	X	X	...	X	X	...
		Systems in study[b]	Ex	Ex	Ex	...	...	...	Ex	...
Elasticized polyolefin	TP	Factory	...	...	...	X	...	...	X	...
		Field	...	...	...	X	...	...	X	...
		Systems in study[b]	...	...	...	...	...	...	Ex[c]	...
Ethylene propylene rubber	XL	Factory	...	...	...	X	X	...	...	...
		Field	...	...	...	X	X	X	...	...
		Systems in study[b]	...	...	...	...	Ex[c]	...	...	...
Low-density polyethylene	TP	Factory	...	...	...	X	...	...	X	...
		Field	...	...	...	X	...	X	X	...
		Systems in study[b]	...	...	...	...	...	...	...	...
Neoprene (polychloroprene)	XL	Factory	...	...	...	X	...	...	...	...
		Field	...	...	...	X	...	...	...	...
		Systems in study[b]	...	...	...	Ex	...	...	...	...
Poly(vinyl chloride)	TP	Factory	X	X	X	X	...	...	X	X
		Field	X	X	X	X	...	X	X	...
		Systems in study[b]	Ex	Ex	Ex	...	...	...	Ex	...

[a] XL = Crosslinked or vulcanized; TP = thermoplastic.

[b] Adhesive systems in the exposure tests. Most of the seams that were exposed were made in the laboratory.

[c] Includes the factory-made seams.

humidity, and wind. Volatile solvents which may be desirable at lower temperatures will evaporate too quickly at higher temperatures or may fail to bond because of moisture condensation under humid conditions.

Bodied Solvents

Similar to solvent "welding" is the use of bodied solvents to seam lining materials. A bodied solvent is essentially an adhesive based upon a solution of the liner compound to be seamed. The adhesive needs to be applied to both surfaces and the two surfaces pressed together after becoming tacky. There should not be evidence of surface "skinning" or drying of the adhesive when the two surfaces are joined. The basic advantage of a bodied solvent over a straight solvent is the increased viscosity of the solution which allows more control of the evaporation of the adhesive and aids in making seams on a slope. As with solvent "welding", this tecnhique can only be used with thermoplastic materials that can be dissolved in a suitable solvent. The manufacturers who supplied the CSPE sheeting used for a primary test specimen also supplied an adhesive which they stated was a bodied solvent. This technique can be used to seam sheeting both in the field and in the factory.

Solvent Cements and Contact Cements

"Solvent cements" is an expression used by the adhesive industry to refer to any of a large variety of adhesives that are applied dissolved in a nonaqueous solution. The strength of the bond is achieved either contemporaneously with or after the volatization of the solvent. Thus, a solvent cement can be anything from a solution of a thermoplastic resin to a contact cement. Two types of solvent cements are of interest to the lining industry:

- Contact cements.

- Cements that volatilize their solvent while forming the adhesive bond.

Surfaces to be bonded by the second type of adhesive are usually pressed together while the solvent cement is still "wet". Because polymeric membrane materials can have low permeability to a number of solvents, it is important to choose a solvent cement based on a solvent that can volatilize out of the seam assembly. This can happen when the solvent in the cement either dissolves or partially dissolves the surface of the sheeting and forms what might be called an "interpenetrating" bond with the lining material. Two adhesives of this type were used for forming the seams in some of the CPE buried test specimens.

Contact cements are adhesives that are applied wet to surfaces of sheetings that are to bonded and allowed to dry to a "tacky" and solvent-free state before the two surfaces are joined. The use of this type of adhesive requires careful alignment of the lining material before bonding because the joined surfaces should not be realigned after assembly. After joining, the seam should be rolled with a steel or plastic roller in a direction perpendicular to the edge of the seam.

The adhesives used with the PVC primary test specimens are described as contact cements. The adhesive used with the neoprene buried test specimen could also be classified as contact cement.

All solvent cements can be used either in the field or in the factory, although with a thermoplastic material it would more likely be used in the field.

Vulcanizing Adhesives

Vulcanizing adhesives achieve their strength from the crosslinking or vulcanization of the polymeric base. The vulcanization may be either a long or short-term operation and may occur under service conditions. Usually, a vulcanizing adhesive is a two-part system, one containing the polymer base, and the other the crosslinking agents. One such system was used to seam the butyl primary test specimens and to seam all of the butyl and some of the EPDM buried test specimens. The complete system, as supplied by the manufacturers, included a two-part cement, a rubber-base gum tape, and a lap sealant. The lap sealant was applied to the butyl primary test specimen, but was not used with any of the buried test specimens. The two-part cement, described by the manufacturer as a "high-strength contact cement", was mixed, applied to both surfaces to be bonded, and allowed to dry until it did not stick to the back of a finger. The gum tape was first applied to one of the surfaces, which was then allowed to fall into place on top of the second surface. The liner manufacturer claimed the gum tape would be cured by vulcanizing agents migrating from the cement to the gum tape. This system was designed for use in both the factory and the field.

Tapes

A convenient way to seam membrane lining materials in the field is to use tapes which are usually made with pressure-sensitive adhesive applied either to both sides of a flexible substrate or to a flexible backing. The latter is removed once the tape has been placed on one of the surfaces to be joined. Tapes can be used to hold the sheetings in place while another seaming technique is used, or they can be used to provide the permanent bond. Tapes have been used to seam polyethylene liners in the field. No seams of this type were used in this project.

Thermal (Heat) Techniques

A number of different techniques utilizing heat can be used in the factory or in the field. The surfaces to be seamed are melted and pressed together to form a homogeneous bond. One technique works by directing high temperature air between two sheets in an overlap seam followed by a pressure system. Another variant of heat seaming is dielectric seaming, which is a factory process involving the use of high-frequency dielectric equipment to generate heat and pressure on an overlap seam joint. In seaming the low-density polyethylene primary test specimen and one of the polybutylene buried test specimens, we used a Harwil T-bar plastic sealer which melts a 1/8-inch wide, 13-inch long strip from above to form a bond. An aluminum strip had to be pressed on top of the seams immediately after the heat sealer was lifted up to prevent the seamed material from "crinkling up" while cooling. Thermal techniques are only used to seam unvulcanized material. Methods have been developed, and are continuing to be developed, so that heat techniques can be used to seam lining materials in the field. The width of the typical industrial liner heat seals as manufactured by liner fabricators is in the order of 1/2 to 1 in.

POTENTIAL PROBLEMS WITH FIELD SEAMS

When problems occur with field seams, they usually fall into one of four categories:

1. Adverse weather conditions, i.e., temperature, wind, and humidity.
2. Improper preparation of the surfaces of the membranes to be seamed.
3. Inability to control the adhesive systems properly under the ambient conditions.
4. Bonding system not suitable for service conditions of the liner.

Inadequate surface preparation ultimately prevents the development of a good bond between two sheetings. The type of surface preparation necessary depends on the type of material being seamed and how the sheeting was manufactured. For instance, the EPDM sheeting used as a primary test specimen had been dusted with talc to prevent blocking and had to be buffed. In general, the surfaces must be free of dirt and foreign materials, including migrating plasticizer, water, dust, oil, and grease. The manufacturer of the CSPE sheeting used as a primary test specimen required that the surfaces be cleaned with trichloroethylene or perchloroethylene to remove a surface cure. The maximum amount of time allowed to elapse under ideal conditions before the two surfaces were to be bonded was set at ten mintues. The manufacturer of the EPDM and PVC sheeting supplied us with specific solvents that were to be used to wash the splice areas. One difficulty that arises with the use of a solvent wash is that moisture condenses on the sheeting surface because of the cooling effect of the evaporation of the solvent. This moisture should be allowed to evaporate before the surfaces are brought together.

When using an adhesive or a solvent, care must be taken to apply the adhesive evenly and completely on the surfaces of the sheeting to be seamed and to press the surfaces together within the tack life of the adhesive being used. Most problems with using solvents as a bonding system in the field are related to their relatively quick evaporation which can be quickened by wind and higher temperatures. To make the application of solvent as quick as possible, a squeeze bottle is sometimes used to squirt solvent between the overlapped sheets. The two sheets are then pressed together. The manufacturer of the CSPE primary test sheeting required that their adhesive, essentially a bodied solvent, be "thoroughly wet" on both surfaces at the time they were joined. The cements used to seam the EPDM, PVC, and butyl primary test specimens had to dry to a finger touch. When these cements were dry, the surfaces had to be checked for the presence of any water condensation that might have resulted from cooling caused by rapid solvent evaporation in highly humid conditions.

In seaming thermoplastic sheeting by solvents or by thermal methods, the objective is to achieve flow or migration of the materials across the interface on a molecular scale. At lower temperatures, solvents cannot swell or dissolve a membrane surface to make it tacky. Therefore, some manufacturers require the use of artificial means to heat both the sheeting and the adhesive if the ambient temperatures is below 60°F. Variations in temperatures in the field can affect the functioning of thermal equipment because the heat required to fuse the surface of the sheeting will vary with the temperature of the sheeting and the ambient conditions. The heating must be adjusted for each seaming operation and then checked periodically in the course of the seaming operation. It is inadvisable to seam at temperatures below 50°F, but if necessary means should be taken to pre-heat the sheeting and to work under a cover such as a mobile tent.

EXPOSURE TESTING OF SEAMS

In view of the importance of seam integrity to the overall performance of liners in the field, seams were incorporated in the primary liners that were placed in the bases of the simulators using the procedures recommended by the respective manufacturers. In addition, small test joints were incorporated in the strip specimens that were buried in the sand above the primary specimens mounted in the bases. These strip specimens embody a range of different seaming systems which included those that had been incorporated in the primary liner specimens. All of the seams made in the laboratory, except the heat-sealed seams, were two inches in lap width. The widths of the heat-sealed seams made with the Harwil T-bar plastic sealer were only as wide as the heated element, i.e., approximately one-eighth inch.

Bonding Systems

The various bonding systems that were used are indicated in Table 37; they are limited in number compared with the types that were potentially usable in seaming. Included were some seams that were part of the sheetings as supplied. Many of the bonding systems exposed in the buried coiled strips had not been recommended by the manufacturer for use with the specific sheeting; they were tested strictly on an experimental basis. No tapes and dielectric seams were incorporated in the test and no heat seams were prepared in the laboratory with heat guns, although one of the factory seams was fabricated with the use of a heat gun.

Testing of Seam Strength

Seam samples were tested for strength in both peel and shear modes. No attempt was made to follow any given ASTM standard exactly because most of the standards are designed to measure the strength of an adhesive rather than the strength of a seam and because the ASTM specimens have to be prepared in ways that were not appropriate to the scope of this project. For testing, the specimens were cut into approximately one-inch-wide strips. In the case of the seams in the primary liners, two specimens were tested in the peel mode and two in the shear mode. The buried strip specimens were only 2.1 inches in width; therefore, only two specimens could be tested, one each in peel and shear modes. All specimens, whether in peel or shear modes, were tested at crosshead speed of two inches per minute at 23±2°C. Specimens were tested in both modes because 1) peel strength is more sensitive to the effects of aging and exposure, and 2) the shear mode reflects the more usual condition of a seam in service. A combination of the two modes, therefore, appears appropriate for monitoring the behavior and durability of a seam in the field.

The type of peel test used was the "T-peel" (cf. ASTM D1876). During the testing of the shear specimens, no attempt was made to keep the entire specimen in the plane of the clamps by holding the specimen against a plate attached to the stationary clamp as required in ASTM D816, Method B. All data are reported in pounds per inch width of the tested specimen. Testing was done within a month after removal from exposure. Specimens were kept damp until testing by storage in sealed polyethylene bags into which some water was placed.

Results of the Exposure Testing

The detailed test data for the seams in the primary liners and in the buried strip specimens are reported in Appendix I. Included are data on seam strength in peel and shear modes for the unexposed seams and, in most cases, for two exposure periods, 12 and 56 months. The adhesion system is identified by the type (e.g., solvent, heat, cement), the place where it was fabricated (i.e., laboratory or factory), and other details. The data are reported in pounds per inch width of seam and the locus of failure is indicated.

Observations and Conclusions

This study of membrane adhesion and seam strength must be considered as exploratory. Although a variety of systems and a relatively large number of specimens were made and exposure tested, the testing itself was actually limited. There were few replications compared with the number normally required in adhesion studies. The principal purpose of the study was to assess the adhesion systems that were recommended by the membrane manufacturers. It was recognized that these systems were not necessarily optimized and that fabricators using proprietary systems and techniques could make superior seams to those recommended by sheeting manufacturers. Variations were introduced in the study to help point out any serious problems in adhesion and in the exposure of these seams to MSW leachate. However, it is possible to make the following observations and conclusions based on the test results:

1. With most seams there was a drop in seam strength with exposure time, although with some seams, such as of the vulcanized rubber sheeting with the two-part vulcanizing adhesives, there were small increases.

2. Overall, the thermoplastic sheetings with fabric reinforcement, which can be heat sealed and bonded with solvent or bodied solvent, give the highest values in the adhesion test in the shear modes.

3. The thermal adhesive systems and some of the bodied solvent systems, in which the liner compound is dissolved in a solvent, appear to

give the best results; however, results will vary with the polymer. A crystalline polymer will not dissolve in the solvent at normal temperatures; therefore, it must be seamed with heat. Other materials, such as the PVC materials, can be thermally sealed as well as seamed by solvent welding, with cements, or with bodied solvents.

4. The peel strength of a seam is more sensitive to aging and exposure than is the shear strength, particularly when an adhesive is used. In many cases, the peel values will drop considerably even though there is no appreciable loss in shear strength values. A constant high value in shear strength, therefore, may not indicate a deterioration that is taking place in a bond. For durability studies, it is particularly important to use peel tests in evaluating a seam.

5. Specific adhesion systems need to be selected on the basis of the material to be seamed.

6. The differences in the results obtained from the buried strips and from the primary liners shows the sensitivity of some of the systems to fabrication workmanship, even when following manufacturer's recommendations. The seam in the CSPE primary liner had considerably lower seam strength than did the seams on the strip specimens which were buried although both were made by the same technician.

7. No apparent variation developed in the seam strength of replicate seams or joints from one simulator to another. This indicates that the exposure conditions in the simulators were essentially equal.

SECTION 12

RECOVERY AND TESTING OF SAMPLES OF A POLYVINYL CHLORIDE LINER FROM A DEMONSTRATION LANDFILL

Information regarding the performance of lining materials in extended service in MSW landfills with exposure to leachate has been very limited. First, the lining of landfills, particularly with flexible polymeric membranes, is relatively new, i.e., from the early 1970's. Second, effective and economic methods have not been developed for sampling and repairing the linings at the bottom of landfills.

An opportunity to sample and repair a lining at the bottom of a landfill became available in a demonstration landfill in Crawford County, Ohio, which had been placed in the spring of 1971 and was lined with a polyvinyl chloride sheeting (Jones, 1973). The liner was relatively accessible, since the total fill consisted of one lift of 8 feet of refuse, and the total depth of the landfill, including the soil cover, was about 12 feet. This demonstration landfill had been designed to compare conventionally-processed solid waste with a shredded waste and a rough compacted waste (Figure 18). The various types of refuse had been placed in essentially waterproof cells lined with a PVC membrane. The effect of water content on consolidation and decomposition of the refuse was to be determined. However, all of the cells were flooded with water in a heavy rainfall just before the fill was closed. Thus, the original objectives could not be met and the project was terminated.

In view of the relative accessibility of the liner and its age in service, the landfill was opened in May 1977, six years after it had been constructed, and samples of the membrane liner were recovered. The three-foot thick topsoil cover was first removed to expose the top membrane liner which covered the cell. The liner was quite rough, reflecting either the irregular compaction of the six-inch soil cover placed directly on the waste or the settling of the soil and refuse beneath it.

A backhoe was used to dig the hole into the refuse, which, though it had been drained, appeared to have been completely saturated with water immediately before the excavation. The condition of the refuse did not appear to be typical of that in MSW landfills; it showed little deterioration and had only a mild odor.

The samples of PVC liner recovered from the cells appeared to be in excellent condition with little difference apparent between samples taken from the top of the cell, above the refuse, and those taken from the bottom, below the refuse. The top liner had been under 3 feet of clay cover, and the bottom liner had been under about 2 feet of clay and on top of pea gravel. Both

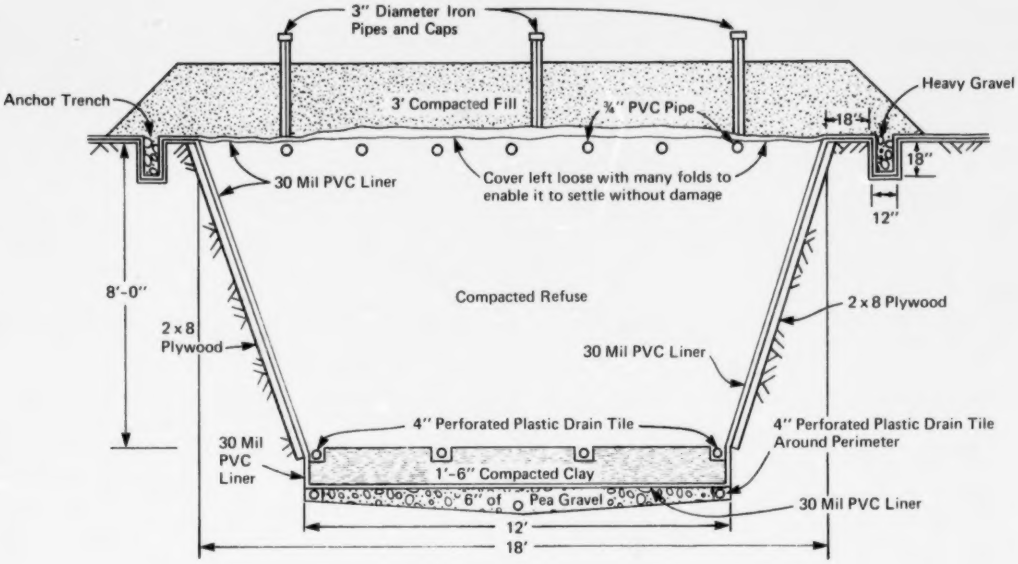
3" Diameter Iron Pipes and Caps
Anchor Trench
3' Compacted Fill
¾" PVC Pipe
Heavy Gravel
18"
18"
12"
30 Mil PVC Liner
Cover left loose with many folds to enable it to settle without damage
8'-0"
Compacted Refuse
2 x 8 Plywood
2 x 8 Plywood
30 Mil PVC Liner
4" Perforated Plastic Drain Tile
4" Perforated Plastic Drain Tile Around Perimeter
30 Mil PVC Liner
1'-6" Compacted Clay
6" of Pea Gravel
30 Mil PVC Liner
12'
18'

Figure 18. Cross-section of cell showing positions of the PVC liner and the compacted clay liner at the bottom (Jones, 1973).

liners had taken the shape of soil and gravel without being punctured or broken. The depressions were as much as 6-inches deep in a one-foot area in the exposed liner taken from the top of the cell (Figure 19). The sample taken from above the pea gravel, which had been crushed and was sharp, showed the imprints of the gravel, but had no holes (Figure 20).

The recovered samples were analyzed along with a sample of polyvinyl chloride sheeting that was thought to have been from the same lot of material as that used for lining the cells. However, test results (Table 38) showed that the two specimens taken from the fill were very similar and considerably different in composition from the unexposed sample, indicating that the latter could not be used as a control for the exposed liner. As Tables 38 and 39 and the results of immersion tests (Section 9) show, the amount of swelling and the decrease in properties of the lining were within the spread of values observed in the leachate immersion test for polyvinyl chloride liner materials. The sample taken from the bottom of the landfill was probably not in direct contact with the leachate in the fill during the 6 years it was in place. The two-foot soil layer above the liner was a highly impermeable clay, having a permeability coefficient of 1.4×10^{-7} cm/sec (Table 40). The clay layer and the weak leachate created a situation that was not typical of what might be anticipated for a liner in a full-scale MSW landfill.

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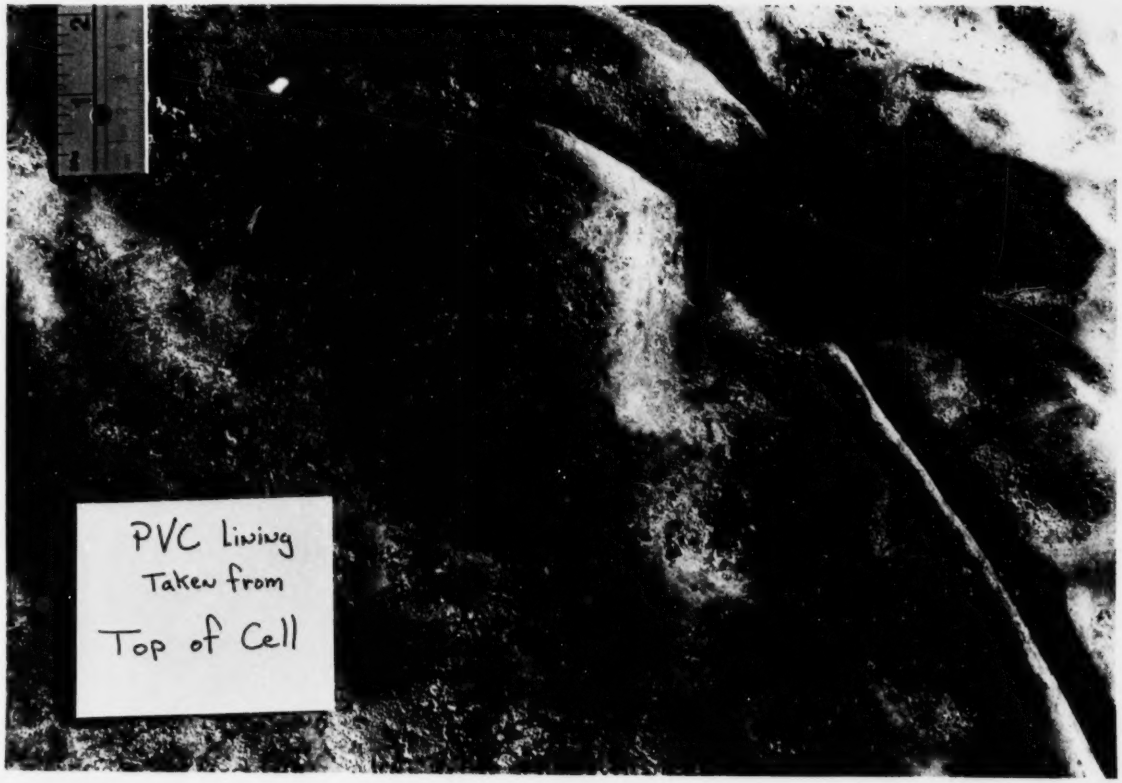
PVC Lining
Taken from
Top of Cell

Figure 19. Sample of PVC lining taken from the top of the cell. Photograph shows the folds in the sheeting and the draws due to the irregularity of the soil. No puncture or splitting of the sheeting was observed.

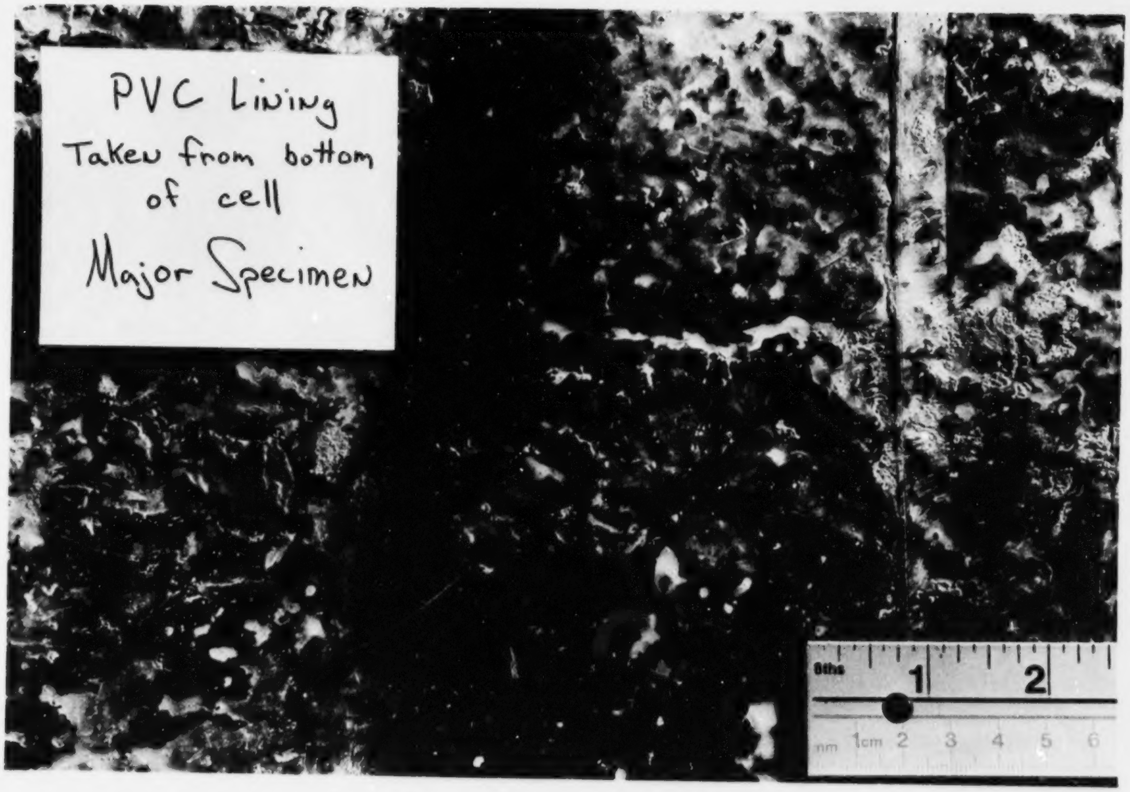
PVC Lining
Taken from bottom
of cell
Major Specimen
8ths
1
2
mm
1cm
2
3
4
5
6

Figure 20. Sample of lining taken from the bottom of the cell. The imprint of the pea gravel on which the sheeting rested can clearly be seen. No punctures were observed. Also shown is a seam one-half inch wide.

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TABLE 38. ANALYSES OF POLYVINYL CHLORIDE LINER RECOVERED FROM A DEMONSTRATION LANDFILL IN CRAWFORD COUNTY, OHIO

Liner number Exposure	95 Unexposed[a]	96 Top of fill	97A Bottom of fill
Volatiles, (2 h at 105°C), %	0.10	0.41	1.33
Specific gravity (dry basis)	1.379	1.260	1.265
Ash (dry basis), ASTM D297, %	10.26	6.14	6.01
Extractables (dry basis), ASTM D3421[b], %	7.54	34.10	34.43
Pyrolysis			
Polymer and organic, %	80.6	87.0	89.0
Polymer, %	73.1	52.9	54.6
Carbon black	8.6	6.7	4.4
Ash, %	10.9	6.4	6.8

[a] 30 mil PVC sheeting thought to have been from the same lot of material as that used to make the liner.

[b] Modified procedure: Refluxed 20 h with mixed solvent of carbon tetrachloride (CCl_4) and methyl alcohol (CH_3OH) 2:1.

TABLE 39. PROPERTIES OF PVC LINER RECOVERED MAY 1977 FROM DEMONSTRATION LANDFILL IN CRAWFORD COUNTY, OHIO

Liner number Exposure Direction of test		96 Top of cell Machine	 Transverse	97A Bottom of cell Machine	 Transverse
Thickness, mils	ASTM D412	30	...	28	...
Tensile strength, psi	"	2665	2600	2550	2475
Elongation at break, %	"	340	360	325	350
Tensile set, %	"	66	79	55	70
S-100, psi	"	1290	1245	1185	1085
S-200, psi	"	1830	1750	1785	1605
S-300, psi	"	2245	2300	2400	2205
Tear strength, ppi	ASTM D624	374	370	343	341
Hardness, Durometer points 5 second reading	ASTM D2240	70A	...	72A	...
Puncture resistance, lb	FTMS 101B Method 2065	41.4	...	37.3	...
Elongation, in.		0.66	...	0.65	...
Seam strength (shear), ppi	...	49.5	...	45.5	...
Locus of failure[a]		SE	...	SE-BK	...

[a] SE = Break at seam; BRK = break in tab.

TABLE 40. PERMEABILITY[a] OF SOIL SAMPLES TAKEN FROM DEMONSTRATION LANDFILL, BUCYRUS, CRAWFORD COUNTY, OHIO

Sample	Core number	Coefficient of permeability, cm/sec
Soil from above PVC liner[b]	1	1.9×10^{-7}
	2	9.4×10^{-8}
	Average	1.4×10^{-7}
Soil from below PVC liner[c]	1	4.9×10^{-8}

[a] Back-pressure permeameter.

[b] Sample from soil compacted above the liner.

[c] Sample of the undisturbed soil below the liner.

A satisfactory repair of the hole could not be made using the unexposed sheeting and a solvent welding system of toluene and tetrahydrofuran. The flow of water in the area could not be stopped; the ground surface on which the liner rested was irregular and the patch material was too stiff to conform to irregularities of the exposed sheeting. A repair system which can take into account these difficulties should be developed in order to insure the integrity of a liner that has been sampled or in some way damaged.

SECTION 13

METHANE PRODUCTION IN SIMULATORS

Toward the end of the operation of the simulators it was observed that the leachate collection bags would become highly inflated and that pressure built up in the cavities of the bases below the liner specimens, indicating the generation of gas, presumably carbon dioxide and methane. A test for methane confirmed its presence in the gas that was generated. In view of the gas-tight quality of the simulator, except for the top, it was felt that a simulator of this design would be useful in the study of methane generation in MSW waste as well as being used to test liner performance. Consequently, an exploratory study was performed to demonstrate the feasibility of this design for future possible use.

The first attempt to monitor the evolution of methane gas was done in March 1979 on Simulator #2. This simulator had been supplied with the highest rate of urea, 226 g. every two weeks, to stimulate the microbial growth and thus the rate of refuse decomposition and methane production.

In order to collect the methane, the generator was sealed with a Lucite cover sandwiched by a double ring (wood and steel) on top and a rubber gasket at the top edge between the simulator and the 0.25-inch thick polymethacrylate (Lucite) plate. The first observation indicated the presence of methane. Subsequently, Simulator #10 was also sealed. The purpose of choosing this simulator for methane monitoring was that it had never been fertilized with urea as we were doing with the other eleven simulators. The idea was to have a "control" for comparison with Simulator #2 which was receiving 226 g urea every two weeks.

In March and April 1979, gas samples were collected from both simulators in specially fabricated polybutylene bags. All samples indicated the presence of methane as determined with a Gastechtor Hydrocarbon Surveyor, Model 1238, manufactured by Johnson Instrument Division of Gas Tech, Inc., Mountain View, California. The results were nevertheless quite erratic. We realized that the inconsistency of the results was mostly connected with the differential loss of methane via diffusion through collecting bags. Subsequently, we used Mariotte-glass collecting bottles, and a Model NP-204 methane detector produced by the same manufacturer (Johnson Instrument). About 10 samples, collected over a period of two weeks, indicated consistently that half of the gas volume in the head space of both simulators was methane.

In order to monitor the rate of methane generation, the following procedure was observed in the case of Simulator #10:

One of the two outlets of the Lucite plates was connected to a water manometer and the other, which was vented to the atmosphere through a cotton plug for 10 days prior to monitoring, to the gas detector. Methane concentration by volume was determined to be 45.5%. The device was then disconnected and the outlet clamped off.

After 22 hours, the manometer indicated a pressure in the head space above the cover on the waste of 32.0 cm water and the methane content was 49.0% by volume.

In our calculations of methane production, the following assumptions were made:

1. Bulk density of the refuse is equal to 1 g cm^{-3}.
2. Liquid content of the refuse is equal to 50% of total refuse porosity.

The number of moles of methane produced is given by:

$$M_{CH_4} = (P_1V_1 - P_0V_0)/RT$$

where:

P_1 = Manometer reading = 1.032 atm.

P_0 = Manometer reading at time = 0; P_0 = 1 atm.

V_1 = Volume occupied by methane in the gas phase = 132.37 liters.

V_0 = Volume occupied in the gas phase at time = 0; V_0 = 122.91 liters.

R = Gas constant = 0.08205 L · atm deg K^{-1} $mole^{-1}$.

T = Kelvin temperature = 293K.

Using this relationship, the rate of methane generation is:

$$Y_{CH_4} = 0.363 \text{ mole } kg^{-1} \ yr^{-1}$$

where Y is the methane yield in moles per kilogram of refuse per year. The rate varies with time since CH_4 production depends, among other factors, on the concentration of organic acids which changes with the age of the landfill.

This example has been presented to show that, for our system, methane generation rates could be monitored. However, in order to obtain reliable data, a more comprehensive research program would be needed. We conclude that it is feasibile to use landfill simulators similar in construction to those used in this project for studies of methane generation in shredded municipal solid waste.

SECTION 14

DISCUSSION OF RESULTS

In the course this project, approximately 65 materials were subjected to at least one of 7 different exposure tests. These materials include 4 admix materials, 2 asphaltic membranes, 50 commercial polymeric membrane liner materials, and 9 miscellaneous materials. The scope of these tests is presented in Table 41. In this section the results of these exposures are discussed and summarized by type of material. The effect of the long exposure is emphasized. Detailed results from all of the exposures are presented in Appendixes B-1, B-2, and Appendixes D through I.

TABLE 41. SCOPE OF EXPOSURE TESTS

Type of exposure	Number of liners	Type of liner or material	Length of exposure, months
Primary, in simulators	6	Polymeric membrane	12, 56
	4	Admix	12, 56
	2	Asphaltic membrane	12, 43, 56
Buried, in simulators	31	Polymeric membrane	12, 13, 43, 56
	9	Miscellaneous materials	12, 43, 56
Immersion, in tanks	28	Polymeric membrane	8, 19, 31
Pouch test:			
With leachate	14	Polymeric membrane	11-40
With NaCl solution	12	Polymeric membrane	10-38
Water absorption (ASTM D570)			
At room temperature	11	Polymeric membrane	43
At 70°C	11	Polymeric membrane	43

ADMIX AND ASPHALTIC MATERIALS

The results (Appendixes B-1 and B-2) from the exposure of the admix and asphaltic lining materials to MSW leachate indicate that, in spite of the fact that asphalt did not appear to have deteriorated in the exposures and that the asphaltic liners did not seep leachate, there may be problems in the use of asphaltic materials for the lining of municipal solid waste landfills.

The permeability of the various asphaltic liner materials did not increase, and the changes in properties of the extracted asphalts were small compared with the changes that occurred in air aging of the same asphalt; nevertheless, the three admix liners containing asphalt changed significantly in the properties of the liners themselves. There was major absorption of leachate or water which resulted in significant decreases in the compressive strength of the asphalt concretes and the soil asphalt. The two asphaltic membrane liners changed significantly also. The canal-lining asphalt, based on catalytically-blown asphalt, absorbed water or leachate and became cheesy and lost elongation. The emulsified asphalt absorbed more water or leachate than the catalytically-blown asphalt, but it appeared to retain its strength because of the presence of the fabric. The greater absorption may be due to the presence of asbestos and water soluble salts in the emulsified asphalt.

The exposure period of this study was only 56 months; however, the results indicate that the asphaltic-based liners would continue to change with prolonged exposure. The complete loss of strength and elongation can be expected to have adverse effects upon the functioning of lining materials, particularly if any ground movement takes place.

There are no ready explanations for the deterioration of all of the asphaltic lining materials. Possibly, a high salt concentration in the asphalt itself may cause swelling by osmosis. The effects of exposure on the asphalt concrete may reflect the particular aggregate that was used, although the Watsonville granite has not been found to cause "stripping", a problem encountered with many aggregates used in road building. The continuous and prolonged exposure of these asphaltic materials to water and to leachate is a condition which is not normally encountered in many asphaltic products. Even in the case of water reservoir linings, the exposure is often intermittent. Also, some asphalts may be more resistant to deterioration upon exposure to MSW leachate; if so, specifications would have to be developed to make certain that the appropriate types are used.

The exposure of soil cement to the MSW leachate did not appear to have any adverse effects upon the soil cement liner specimens. If anything, the soil cement probably gained in strength during the exposure. However, the initial permeability of the unexposed material was relatively high and somewhat erratic; though it appeared to decrease during the first 12 months, it was higher after 56 months of exposure. The soil cement liner, shortly after preparation and cure, could not be cored, and it was necessary to use our laboratory molded specimens for determining the properties of unexposed soil cement. The exposed liner specimens, after 12 and 56 months, yielded good cores that were tested for water permeability and compressive strength. With regard to our results and the use of soil cement as a liner for waste disposal sites, it must be recognized that soil cement is brittle and that the specimens exposed in this project were only 22 inches in diameter. Large areas of soil cement, such as those used as bases for highway pavement, develop cracks every few feet. Because major cracking cannot be tolerated in the lining of a waste disposal site, this tendency to crack eliminates the use of soil cement for the lining of large waste disposal sites.

FLEXIBLE POLYMERIC MATERIALS

The range of flexible polymeric membrane materials and the various exposures to which the specific materials were subjected are listed by type of polymer in Table 42. In all, 50 different polymeric membranes are listed. The results of the exposure tests of the polymer types that were the primary liners are discussed first, followed by a discussion of the polymer types that were tested, but were not primary liners.

Butyl Rubber

Five different butyl rubber lining materials were included in this project; all were vulcanized and one was fabric reinforced. They ranged in nominal thickness from 35 mils for the fabric reinforced liner to 90 mils for one of the unreinforced. Various butyl liners were tested under all the exposure conditions except the pouch test which was not performed because durable, narrow seams could not be made. All of these materials exhibited only moderate effects after exposure to leachate, salt solution, and water. The primary liner, which had a nominal thickness of 63 mils, showed little change in tensile properties, only modest absorption of the leachate, and an increase in puncture resistance (Table 16, Appendix D). The buried sample of the same material yielded comparable results. The other 2 buried specimens of butyl rubber also showed relatively little change in properties (Appendixes E and G).

In the immersion tests, one butyl rubber liner was tested and at 31 months it retained 92% of its tensile and 91% of its elongation (Appendix H). In water absorption, the butyl rubber liner absorbed approximately 11% at room temperature and 141% at 70°C in 43 months (Table 25).

Adhesion and seam strength are major problems with this type of liner material. Low temperature vulcanizing adhesives must be used. These adhesives do not yield high seam strengths, and can be more sensitive to a waste fluid than the liner itself (Appendixes E and I).

Chlorinated Polyethylene

Six different CPE membranes were tested in this program; all were thermoplastic and one was reinforced with nylon. They ranged in thickness from 14 to 32 mils. CPE membranes were included in all of the exposure tests: one was in the primary test, four were buried, four were in the immersion test, two were in the leachate pouch test, two were in the sodium chloride pouch test, and one was in the water absorption test. However, no single membrane was included in all the tests.

The CPE primary test specimen was 31 mils in thickness and unreinforced. During the 56 months of exposure, it absorbed 8.2% by weight of leachate (based on 7.6% volatiles) and its properties generally decreased (Table 16). Of the six primary membrane liners tested in the simulators, the CPE sheeting showed the largest (but moderate) changes in properties with exposure time (Appendix D). The response to the exposure of the buried specimen of the same CPE liner was similar to that of the primary liner, although the effects were slightly greater.

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TABLE 42. SUMMARY LIST OF EXPOSURES OF FLEXIBLE MEMBRANE LINERS EXPOSED TO MSW LEACHATE, SALT SOLUTION, AND WATER

Polymer	Liner number[a]	Fabric	Nominal thickness, mils	Exposure condition					
				Primary barriers	Buried specimens	Immersion	Pouch		Water absorption[b]
							Leachate	NaCl	
Butyl rubber (IIR)	7	-	61-65	x	x	-	-	-	-
	22	-	60	-	x	-	-	-	-
	24	-	90	-	x	-	-	-	-
	44	-	68	-	-	x	-	-	-
	57R	Nylon	35	-	-	-	-	-	x
Chlorinated polyethylene (CPE)	12	-	30-32	x	x	x	-	-	-
	13R	Nylon	30	-	x	-	-	-	-
	23	-	14	-	x	-	-	-	-
	38	-	32	-	(c)	x	-	-	-
	77	-	29	-	-	-	x	x	x
	86	-	22	-	-	x	x	x	-
Chlorosulfonated polyethylene (CSPE)	3	-	31	-	x	x	-	-	-
	4R	Nylon	31	-	x	-	-	-	-
	6R	Nylon	31	x	x	x	x	x	x
	14R	Nylon	36	-	x	-	-	-	-
	55	-	33	-	-	-	x	x	-
	85	-	33	-	-	x	-	-	-
Elasticized polyolefin (ELPO)	36	-	23	-	(d)	x	x	x	x
Ethylene propylene rubber (EPDM)	8	-	62	-	x	x	-	-	x
	16/18	-	49-53	x	x	x	-	-	-
	25	-	56	-	x	-	-	-	-
	26	-	25	-	x	-	-	-	x
	41	-	20	-	-	x	-	-	-
	83R	Polyester	39	-	-	x	-	-	-
	91	-	37	-	-	x	-	-	-
	94	-	30	-	(d)	-	-	-	-
Neoprene	9	-	60	-	x	x	-	-	-
	37	-	73	-	-	x	-	-	-
	42R	Nylon	19	-	-	x	-	-	-
	43	-	34	-	-	-	-	-	x
	82	-	62.5	-	(c)	-	x	-	x
	90	-	35	-	-	x	-	-	-
Polybutylene	20	-	8-10	-	x	-	-	-	-
	98	-	8	-	(c)	x	x	x	-
Polyester elastomer	75	-	7	-	-	x	x	x	x
Polyethylene:									
LDPE	21	-	11-12	x	-	x	x	x	-
HDPE	99	-	98	-	(d)	-	-	-	-
Polyvinyl chloride	10	-	34	-	x	-	-	-	-
	11	-	30	-	x	x	x	x	x
	15	-	10	-	x	-	-	-	-
	17		20	x	x	x	x	x	-
	19	-	22	-	x	x	x	x	-
	40[e]	-	33	-	-	x	-	-	-
	59	-	33	-	-	-	x	x	x
	67	-	22	-	(d)	x	-	-	-
	88	-	20	-	(c)	x	-	-	-
	89	-	11	-	-	x	-	-	-
	92A	-	20	-	(c)	-	-	-	-
	93	-	11	-	(d)	-	x	-	-
PVC with pitch	52	-	80	-	-	x	-	-	-
TOTAL	50			6	21+10	28	14	12	11

[a] R = Fabric reinforced.

[b] Water absorption at room temperature and at 70°C, according to ASTM D570.

[c] Buried in Simulator #12 at 43 months

[d] Buried in Simulator #11 at 43 months.

[e] Oil resistant PVC.

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The effects of the 31-month immersion in leachate on the CPE specimens ranged from 70% retention to retentions of over 100%, indicating the differences in the response of the CPE compounds to leachate immersion (Table 23, Appendix H). Similar results occurred in tests on the two sheetings tested in the pouch test with leachate after 40 months (Table 26). One of the same sheetings exposed in the pouch test with the salt solution was less affected (Table 27). In the water absorption test, however, the CPE membrane absorbed significant amounts at room temperature and at 70°C (Table 25).

The seaming of the various CPE test specimens was performed by heat, solvents, and cements. The heat and cement seams retained their initial adhesion best (Appendix I).

In all of the test conditions, the CPE sheetings tended to absorb significant amounts of water or leachate and to soften. Although varying from formulation to formulation they also tended to show significant losses in some properties, e.g., tensile strength, elongation, and tear resistance.

Chlorosulfonated Polyethylene

Six different CSPE membranes were tested; all were thermoplastic and ranged in thickness from 31 to 36 mils. Three of the six were nylon reinforced. CSPE membranes were tested in all types of exposure. The primary CSPE liner had a thickness of 31 mils, was nylon reinforced, and was tested under all of the exposure conditions. Four different membranes were buried, three were placed in immersion, two were in the pouch tests, and one was in the water absorption test. Note: Only "potable grades" of CSPE liners were tested as the industrial grades were not available at the time.

The CSPE liner had the greatest absorption of leachate of the six polymeric membranes tested in the primary exposure. After 56 months it had absorbed approximately 16% leachate (based on 13.9 % volatiles content). The physical properties, however, changed little during the same exposure period (Table 16, Appendix D). The buried specimen of the same composition increased in tensile strength and modulus more than did the primary liner, probably reflecting the greater crosslinking that took place during the exposure even though it did absorb more leachate, that is about 20.5% (Table 20, Appendix G). Note: A higher modulus in a rubber compound is indicative of greater crosslinking.

After 56 months the four buried specimens varied in retention of properties (Appendix G), which generally reflected both crosslinking of the polymer and absorption of leachate. Even though they all softened, they all retained their tensile strengths. There was considerable variation in the retention of properties by the materials exposed in the immersion tanks (Appendix H). One of the unreinforced CSPE's softened considerably; after 31 months of exposure, it retained approximately 50% of its original modulus. In water absorption, after 43 months of exposure, the one membrane in the test absorbed 20% at room temperature, but over 480% at 70°C (Table 25). Note: This was an accelerated test. The supplier does not recommend use of this particular sheeting, based on a potable formulation, for continuous service above 50°C.

Overall, the CSPE liners tended to absorb considerable leachate, but they appeared to crosslink during exposure and yield higher tensile strengths. However, there is a large spread in the responses of these materials to the leachate. In some cases, their softening is pronounced, probably due to the absorption of leachate. These differences point out major variations in compounding.

Ethylene Propylene Rubber

Eight different EPDM membranes were included in the exposure testing. They ranged in thickness from 20 to 62 mils. Six of the membranes were based on vulcanized EPDM compounds, and two were thermoplastic compounds, one of which was fabric-reinforced. EPDM membranes were exposed in all the tests except the pouch test. As in the case of the butyl rubber membranes, the fabrication of small pouches was a problem because of width of the seams necessitated by the use of the low-temperature vulcanizing adhesives. In addition to the specimen in the primary exposure, five different membranes were exposed as buried specimens in the simulators, five in the immersion test, and two in the water absorption test.

The primary EPDM specimen was an unreinforced membrane of 51 mils thickness. During the 56 months of exposure in the simulator it absorbed 5.7% of leachate (based on volatiles content). The effects of exposure upon physical properties were negligible, although there was a slight trend toward softening and a loss in tear strength. The tensile strength and puncture resistance were maintained through the 56 months (Table 16, Appendix D).

The leachate absorption of the crosslinked buried specimens for the 43 months and 56 months exposures ranged from 4.5 to 9% weight increase, and the effects upon properties were minimal (Appendixes F and G). The buried specimen that was from the same lot as the primary specimen showed somewhat greater leachate absorption than the primary specimen, which was reflected in greater elongation at break, lower modulus, and lower hardness (Table 20).

The effects of the exposure in immersion on the EPDM membranes were small. Even though the leachate absorption ranged from 8 to 24% weight increase after 31 months exposure, the tensile strength ranged only from 94 to 111% of the original values, and the elongation from 88 to 138% of the original values (Table 23, Appendix H).

In the water absorption test, after 43 months of exposure, the two EPDM sheetings swelled 3.5% and 3.6% respectively at room temperature and 18.5% and 27.6% respectively at 70°C (Table 25).

Overall, the EPDM membranes absorbed relatively little leachate and changed little during all of the exposures. Also, the variation among the membranes was small. As in the case of the butyl rubber, the seaming of the membranes is a problem because low-temperature vulcanizing adhesives must be used. Such adhesives tend to have lower crosslinking densities than the sheeting, yield relatively low adhesion strength values, and are more susceptible to swelling by leachate.

Polyethylene

A single lot of LDPE film sheeting was included in this test program. Not only was it tested as a primary liner, but it was also used to line all simulators and initially used to make the leachate collection bags. Samples were included in all exposures but the water absorption test. This membrane was 10 to 12 mils in thickness and was unpigmented, that is, it did not contain carbon black.

In all of the exposure tests in which samples of LDPE sheeting were exposed to MSW leachate, the effects of the exposure upon the samples were minimal and most of the results may have been within the testing error for this material. The absorption of leachate was low; the changes in modulus (S-100 and S-200) and tear were also low. Tensile strength appeared to increase; however, the unexposed sheeting had many flow lines and irregularities which may have contributed to its initial low tensile strength. Also, puncture strength appeared to increase during exposure (Table 16, Appendixes D and H).

A single specimen of HDPE was buried in one of the generators at 43 months and, consequently, had only 13 months of exposure. It absorbed essentially no leachate and had no visible change. This type of material became available late in the project; consequently, only a very limited test could be run on it. This sheeting was 95 mils in thickness and very stiff compared to the other flexible materials in the program.

Polyvinyl Chloride

Twelve different polyvinyl chloride membranes plus a PVC liner containing pitch were included in this project. These liners were all thermoplastic and had no fabric reinforcement. They ranged in thickness from 14 to 34 mils. These membranes were tested in all exposures; in addition to the primary liners, nine were tested as buried specimens, five of which were placed in the simulators at the beginning of the program and four were placed 43 months after the program started. In the immersion test, seven membranes were tested; five were tested in the pouch test with leachate and four in the pouch test with sodium chloride solution. Two PVC sheetings were in the water absorption test.

The primary PVC liner specimen was a 20 mil sheeting which also was subjected to all the exposure tests except the water absorption test. In the primary test, the property values of the PVC membrane went through either a maximum or a minimum, depending upon the property (Table 16, Appendix D). This behavior is probably related to the amount of leachate absorbed in the sheeting. At 12 months there was a maximum in leachate absorption and a minimum in the tensile and modulus values. After 56 months of exposure, the leachate absorption (based on volatile content) was down and the plasticizer content was lower than the original value; the tensile strength, modulus, hardness, and puncture strength had increased.

At 43 months, when removed from the simulator, the buried specimen of the sheeting used as the primary liner yielded values in between the 12 and 56 months data for the primary liner (Appendix F). The other buried specimens showed similar behavior in that they absorbed leachate, lost some plasticizer, and generally increased in tensile strength and in modulus (Appendixes E, F, and G).

In the immersion test, there was an initial loss in modulus at 8 months. Values ranged from 9 to 90% of the original values. At 31 months, they all had increased in modulus; five of the seven exposed membranes had retentions in excess of 100% and ranged from 94 to 117% of the original values. It appears that plasticizer is lost during the exposure, causing hardening of the membranes (Appendix H).

In the water absorption test, after 43 months at room temperature, one of the PVC's had lost weight after having increased by approximately 2% (Table 25). After 43 months at 70°C, the same composition had swelled by 165%. The second PVC also reached a maximum in swell at room temperature; at 70°C at 43 months, it had essentially reached a plateau of approximately 27% absorption.

In reviewing these data, one can summarize the results as follows:

1. The PVC liners tend to swell slightly at normal temperatures, but go through a maximum.

2. The membranes soften due to the swelling, but harden as the plasticizer is lost and the swelling is reduced.

A PVC membrane liner, recovered from a small demonstration landfill, but which however had not been in contact with either the refuse or the leachate, appeared to have sustained little change during the six years it had been in service, either as a cover above the refuse or at the bottom below the refuse. Nevertheless, the burial approximated some conditions of a landfill environment.

Neoprene

No membrane of neoprene was placed as a primary liner in the project because of the relatively high cost and the sensitivity to water of the materials available. However, because of their availability and use in lining of ponds that contained oily wastes, six different neoprene membranes were tested, two as buried specimens, four in the immersion, one as a leachate-pouch, and two in the water absorption. These membranes were all vulcanized and ranged in thickness from 19 to 73 mils; one membrane was fabric reinforced.

The sample of neoprene sheeting that was buried in a simulator at the beginning of the program absorbed 6.4% and retained 77% of its tensile strength and 71% of its S-100 modulus after 56 months (Appendix G). The second neoprene sample buried in a simulator was exposed for only 13 months; however, in that time it absorbed 7.1% in weight of leachate and retained 64% of its S-100 modulus (Appendix G).

The immersion test, which included four neoprene membranes, resulted in a spread of 5 to 88% in leachate absorption (by weight increase), 68 to 105%

retention in tensile strength, and 76 to 115% retention of S-200 modulus during 31 months of immersion (Appendix H).

In the water absorption test of two neoprene membranes, there was a 63% absorption in one and a 52% absorption in the second at room temperature. At the higher temperatures, one disintegrated within 23 months and the other disintegrated within 43 months (Table 25).

The neoprene liner materials we tested were sensitive to moisture and swelled considerably in the presence of MSW leachate; they also varied considerably from formulation to formulation.

Elasticized Polyolefin

A single lot of elasticized polyolefin sheeting was tested in immersion, pouch, and water absorption tests. Also, a sample was buried for 13 months in a simulator. This sheeting is a thermoplastic material of 23 mils thickness. In all of the tests run with the leachate, brine, and water, the results showed that the swelling was low and that the change in physical properties was minimal (Tables 27 and 28, Appendixes G and H), except for the sample in the water absorption at 70°C which had begun to lose weight (Table 25).

Polybutylene

Two lots of this material were tested in the project. These two materials were used to prepare the leachate collection bags and both ranged in thickness from 8 to 10 mils. In all tests they showed low absorption and good retention of properties in burial, immersion, and pouch tests (Appendixes F and G, H, and Tables 26 and 27, respectively).

Polyester Elastomer

A noncommercial, experimental polyester elastomer sheeting of 7 mils thickness was tested because of its reported good resistance to oils. It was tested in immersion, pouch, and water absorption tests. In the immersion test it showed drops in tensile strength and elongation and to a lesser extent in puncture resistance (Appendix H). In the pouch test there were similar losses in tensile strength and puncture and tear resistances (Tables 26 and 27). In water absorption, it disintegrated completely at 70°C (Table 25). The surface of the material after exposure rubbed off black, thus showing degradation.

Miscellaneous Materials

Among the several miscellaneous materials that were tested by burial in the simulators, two materials are of particular interest. The first is polypropylene which, like polybutylene and polyethylene, is a thermoplastic, partially crystalline polyolefin. In the exposure to leachate, this material showed very low water absorption and little change in properties (Appendixes E and F). It is, however, a very stiff material and one that would probably be difficult to seam.

The second material of interest is the urethane gasket material. Liquid urethanes have been used as sprayed-on liners in specialized applications. The composition of this particular gasket was not known, but presumably was based upon a polyester. It degraded badly during burial in a simulator, probably by hydrolysis, indicating that some polymeric materials can degrade on a molecular scale and cannot be used as liners of waste disposal facilities for extended service (Appendixes E and F). They must be tested for compatibility with the waste liquid.

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SECTION 15

COSTS OF LINING MATERIALS FOR MSW LANDFILLS

One objective of this project was to estimate the relative costs of various lining materials for MSW landfills. Based on our results and given the proper design of a facility, it appears that a number of technically suitable materials can be selected for the purpose of lining an MSW landfill. Although the liner is only part of the total construction of a landfill facility, its cost can be a significant factor in overall costs. Consequently, the costs of liners will be considered by designers and engineers in their selection of a specific material for an MSW landfill.

GENERAL FACTORS CONTRIBUTING TO THE COSTS OF LININGS

A wide range of factors are involved in the cost of lining materials. Some of these factors are:

- The type of material used. Materials costs are essentially determined by the prices of the raw materials necessary to the manufacture of the liner. An on-site soil, if it is found to be suitable, will probably be the least expensive. A choice between other materials may be made on a cost-benefit basis.

- The location of the facility and the transportation costs involved in bringing the lining material or fill to the site. Liner projects in remote areas with rugged terrain will have higher costs than sites with more favorable topography and geology or located nearer to the source of liner materials.

- As with most construction activities, the time of the year affects labor availability and productivity. In addition, inclement weather can disrupt liner installation. In the case of membrane liners, successful field seaming requires a fairly narrow range of environmental conditions; such liners cannot be placed in excessive heat or cold, snow or rain, or on nonstable or wet ground. Delays in construction and liner placement can thus result. Adverse weather conditions can affect the placement of other liner materials as well.

- The size of the disposal facility can have a significant effect upon the cost per unit area of liner As with most projects and construction materials, the larger the contract, the lower the unit cost of work productivity and materials. Large liner projects usually have significant economies of scale.

- Type of soil on site. Regardless of whether the on-site soil is used as the lining material or as the subgrade for either a liner fabricated on the site or a prefabricated liner, the type and condition of the soil can affect costs. Sand or a soil with a limit on the maximum particle size may be needed as a bedding for membrane liners. A porous soil cover is a necessary part of a landfill liner system. It is needed for leachate drainage and collection and to protect the membrane liner against damage by equipment such as tracked vehicles and compactors that operate above the liners to compact the refuse. However, as all liners for MSW landfills need to be covered, the cost of the soil cover itself will essentially not be affected by the choice of liner.

- The differences in the properties of the lining materials may have a small effect upon the cost of site preparation and installation of liners, particularly in soil compaction and subgrade preparation costs and the need for relatively small particle size bedding on which to place membrane liners. Also, a herbicide may be needed with some liners to prevent puncturing by plant growth under a newly laid membrane.

- Differences in installation costs, such as field seaming of the sheeting or panels into the final liner. Some materials will require more work effort than others. Final installed costs will take into account these differences, however.

During the course of this project cost data were developed in October 1973, updated in 1977, and resurveyed in 1981. Generally, the 1973 and 1977 estimates did not include the costs for site and surface preparation, which are essentially the same for all liner types, nor the costs of the soil cover on the liner needed in landfill construction. The cost estimates for 1980 and 1981 include actual winning bids for liner jobs. Major technological advances have occurred since 1973, as well as large cost increases. The estimates for 1980 and 1981 include subgrade preparation unless otherwise noted.

POLYMERIC MEMBRANE LINERS

Prices for the membrane liners are quoted in a variety of ways:

- As "rolled goods" or sheeting as produced by liner manufacturers.

- As fabricated liners, e.g., those produced by the factory-seaming of sheeting into large panels which are then sold to installers.

- As final installed costs which involve the assembly of the panels at the site.

Due to the structure of the industry, the prices of some liners are quoted in all three ways. When the liner manufacture, fabrication, and installation are performed by a single company, only a single price may be quoted, i.e., installed costs.

As the polymer membrane industry is a minor segment of the polymer industry, raw material costs are set by producers of polymers and of other ingredients of the liner compound. Because polymer materials, in turn, are made of chemicals from petroleum sources, costs ultimately are dependent upon costs of natural gas or crude oil feedstocks. The price increases of these petroleum commodities resulted in the corresponding rise in polymer costs for membrane production throughout the 1970's.

Estimated cost data for polymeric membrane liners are presented in Table 43. The unit costs shown cover the period 1973 - 1980 and reflect installed cost only. They do not necessarily represent the total cost of a liner system, as other system components such as groundwater monitoring wells may be required. Also, the costs presented do not reflect equal service life or performance of the liners.

Since 1980, however, several factors have contributed to the moderation of monomer and polymer prices. First, reduced capital expenditures have severely curtailed demand for polymers in many major markets, such as housing, automobiles, commercial construction, packaging, and aerospace, each of which uses hundreds of millions of pounds of these materials. Second, there is a large over-capacity for chemical polymer production which has led to significant discounting from list prices of polymers. These recent trends are not reflected in the cost data presented.

SOIL, ADMIX, AND SPRAYED-ON LINERS

Cost estimates for soil, admix, and sprayed-on asphalt membrane liners are presented in Table 44. The original data were collected in 1973 and updated periodically. The data for 1980 show the most recent update. As with the polymeric membrane liners, the costs shown include neither the costs for site and surface preparation, nor the costs of a soil cover. Specific cost data for these liner types are difficult to obtain and are heavily influenced by geographic location, especially transportation costs.

The costs for asphalt-concrete liners are closely related to those for asphalt paving concrete. Existing equipment and technology are available which can be used as is or with modification to install liners. Thus, liners of soil or admix materials may be cost effective for lining MSW landfills.

TABLE 43. COSTS OF FLEXIBLE POLYMERIC MEMBRANE, PLASTIC, AND RUBBER LINERS

Material	Nominal thickness, mils	Fabric reinforcement[a]	1973 Price, fob $/yd^2	1973 Installed cost[b] $/yd^2	1977 Delivered cost[c] $/yd^2	1977 Installed cost[b] $/yd^2	1980 Installed cost[b] $/yd^2	1981 Installed cost[b] $/yd^2
Butyl rubber	30	no	2.25	3.25-4.00	2.70-3.15	3.40-3.60	...	...
		yes	...	...	2.79-3.24	...	4.10-4.90[d]	...
Chlorinated polyethylene (CPE)	30	no	2.25	2.43-3.24	2.70-3.15	3.10-3.50	...	...
		yes	...	...	2.79-3.24	3.24-3.78	6.17[e,f]	5.80-10.00[g]
Chlorosulfonated polyethylene (CSPE)	30	no	...	...	2.70-3.15	3.10-3.50	...	...
		yes	1.66	2.88-3.06	2.79-3.24	3.24-3.78	4.70-8.50[h,i,j,k]	5.80-10.00[g]
Elasticized polyolefin (ELPO)	20	no	...	...	1.80	2.07-2.25	...	...
Ethylene propylene rubber (EPDM)								
covered	30	yes	2.00[l]	2.43-3.42	2.70	3.42-3.50	...	...
uncovered	30	yes	...	...	2.16	2.88	4.10-4.90[d]	...
Neoprene (CR)	30	no	2.07	4.41-5.40	...	...	...	...
		yes	...	...	5.00	5.85-6.75	...	...
Polyethylene								
Low-density (LDPE)	10	no	0.36	0.90-1.44	0.60-0.70	1.10-1.40[m]	...	...
High-density (HDPE)	60	no	...	...	...	...	...	6.75[n]
	80	no	...	...	...	...	...	7.20-7.65[o]
Polyvinyl chloride (PVC)	20	no	.90	1.17-2.16	1.11-1.53	1.44-1.98	...	...
	30	no	1.33	...	1.44-1.89	1.80-2.45	...	...

[a] Fabric reinforcement, usually nylon or polyester scrim.

[b] Installed cost is highly dependent on area being lined.

[c] Delivered cost in dollars per square yard; cost of sheeting in panel - 5000 to 150,000 sq. ft.

[d] Installed cost estimate. Key Enterprises for April 1978, 45 mil nylon reinforced.

[e] 45 mil thickness, three ply, one ply polyester scrim.

[f] Engineering News Record, July 10, 1980, p. 61; does not include subgrade preparation on soil cover.

[g] StaFlex Corporation estimate, May 1981, for 30, 36, and 45 mil reinforced CPE and CSPE.

[h] 45 mil thickness, five ply, two ply polyester scrim.

[i] Winning bid, June 11, 1980, City of Seattle, North Beacon Reservoir Reline.

[j] Installed cost Candelaria Silver Project, 30 mil 8 x 8 scrim, $4.70 per square yard, August 1980.

[k] Installed cost Martin Marietta Aluminum Co., 30 mil 8 x 8 scrim, $4.75 per square yard, July 1980.

[l] The cost over the range of area of 150,000-500,000 sq ft is usually in the range of $0.05-0.06 per square foot.

Soil cover: Source 1 - $0.10-.50/yd^2/foot of depth
Source 2 - 0.05-.07/ft^2/foot of depth

[m] If tape is used, tape cost: $0.05-.06/linear foot.

[n] Rubber and Plastics News II, August 24, 1981, for 60 mil thickness.

[o] StaFlex Corporation estimate, May 5, 1981, high-density polyethylene, 80 mil thickness unreinforced.

TABLE 44. COST ESTIMATES OF SOIL, ADMIX, AND ASPHALT MEMBRANE LINERS

Liner type	Installed Cost Dollars per square yard 1973[a,b]	 1980
Soil + bentonite 9 lb/sq yd (1 psf)	$0.72	$1.31[c]
Soil cement 6-in. thick + sealer (2 coats - each 0.25 gal/sq yd)	1.25	2.27[c]
Soil asphalt 6-in. thick + sealer (2 coats - each 0.25 gal/sq yd)	1.25	2.27[c]
Asphalt concrete, dense-graded paving with sealer coat (hot mix, 4-in thick)	2.35 - 3.25	5.00 - 7.00[c]
Asphalt concrete, hydraulic (hot mix, 4 in thick)	3.00 - 4.20	5.46 - 7.64[c]
Bituminous seal (catalytically blown asphalt) 1 gal/sq yd	1.50 - 2.00 (with earth cover)	2.73 - 3.64[c]
Asphalt emulsion on mat (polypropylene mat sprayed with asphalt emulsion)	1.26 - 1.87	1.87 - 3.40[c]

[a] Haxo, 1976 (October, 1973 costs).

[b] Estimated installed costs on west coast.

[c] Costs updated based on Engineering News Record data. Materials cost index for October 1973 was 788.5. Materials cost index for November 1980 was 1433.7.

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APPENDIX A. PROPERTIES[a] OF UNEXPOSED MEMBRANE LINERS

Polymer		Butyl rubber			
Liner number[b]		7	22	24	44
	Direction of test				
Analytical properties					
Specific gravity		1.206	...	...	1.176
Ash (db), %		5.25	...	...	4.28
Volatiles, %		0.45	...	...	0.46
Extractables (db), %		10.96	...	...	11.79
Physical properties					
Average thickness, mils		64	73	99	62
Tensile strength, psi	Machine	1445	1170	1500	1625
	Transverse	1425	870	1500	1570
Elongation at break, %	Machine	365	620	360	415
	Transverse	430	525	430	470
Tensile set, %	Machine	15	73	15	18
	Transverse	19	48	18	18
S-100, psi	Machine	355	290	330	335
	Transverse	290	230	250	280
S-200, psi	Machine	775	430	750	750
	Transverse	615	370	620	615
Tear strength (Die C), ppi	Machine	175	144	205	200
	Transverse	175	140	215	220
Puncture resistance					
Stress, lbs		44.8	47.7	64.9	39.5
Elongation, in		1.22	1.24	1.24	1.18
Thickness, mils		65	75	99	...
Hardness, Durometer points 5 second reading		51A	54A	57A	54A
Exposure conditions[d]		PR, Bu	Bu	Bu	Im

See footnotes at end of table.

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APPENDIX A (Continued). PROPERTIES[a] OF UNEXPOSED MEMBRANE LINERS

Polymer		Chlorinated polyethylene					
Liner number[b]		12	13R	23	38	77	86
	Direction of test						
Analytical properties							
Specific gravity		1.360	...	...	1.336	1.362	1.377
Ash (db), %		14.40	...	...	11.83	12.56	17.37
Volatiles, %		0.10	...	...	0.24	0.00	0.05
Extractables (db), %		7.47	...	...	...	9.13	...
Physical properties							
Average thickness, mils		31	36	16	32	29	22
Tensile at fabric break, ppi	Machine	...	200.0	...	...	...	...
	Transverse	...	151.3	...	...	...	...
Tensile strength, psi	Machine	2465	1315	2510	2190	2055	1845
	Transverse	2085	1005	1160	2000	2340	1510
Elongation at break, %	Machine	305	70	325	340	325	355
	Transverse	515	250	300	505	480	595
Tensile set, %	Machine	199	...	173	192	140	208
	Transverse	230	250	86	201	160	235
S-100, psi	Machine	1220	...	750	1345	1240	870
	Transverse	520	890	480	565	560	275
S-200, psi	Machine	1815	...	1700	1640	1540	1210
	Transverse	840	925	740	770	820	405
Tear strength (Die C), ppi	Machine	270	...	240	250	270	190
	Transverse	240	...	190	210	240	180
Puncture resistance							
Stress, lbs		47.0	70.2	22.8	47.8	43.9	20.9
Elongation, in		1.04	0.31	0.92	0.86	0.94	0.91
Thickness, mils		32	36	16	32	...	22
Hardness, Durometer points 5 second reading		77A	76A	85A	76A	80A	67A
Exposure conditions[d]		PR, Bu, Im	Bu	Bu	Bu, Im	Po	Im, Po

See footnotes at end of table.

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APPENDIX A (Continued). PROPERTIES[a] OF UNEXPOSED MEMBRANE LINERS

Polymer		Chlorosulfonated polyethylene					
Liner number[b]	Direction of test	3	4R	6R	14R	55	85
Analytical properties							
Specific gravity		1.433	...	1.343	...	1.371	1.311
Ash (db), %		33.95	...	3.28	...	3.32	4.02
Volatiles, %		0.84	...	0.51	...	0.42	0.92
Extractables (db), %		1.49	...	3.77	...	4.08	...
Physical properties							
Average thickness, mils		31	33	31	36	35	33
Tensile at fabric break, ppi	Machine	...	83	39	76	...	...
	Transverse	...	63	33	78	...	...
Elongation at fabric break, %	Machine	...	23	30	15	...	...
	Transverse	...	23	15	25	...	...
Tensile strength, psi	Machine	1650	1050	1915	1750	1860	2345
	Transverse	1430	1005	1610	1560	1565	2055
Elongation at break, %	Machine	580	195	250	150	260	260
	Transverse	640	425	245	160	300	325
Tensile set, %	Machine	370	180	119	...	75	167
	Transverse	380	355	106	...	97	192
S-100, psi	Machine	670	945	1005	1750	1110	1150
	Transverse	520	725	855	1540	650	750
S-200, psi	Machine	850	1065	1710	...	1810	2130
	Transverse	620	835	1335	...	1205	1410
Tear strength (Die C), ppi	Machine	290	...	...	...	295	305
	Transverse	270	...	...	...	270	275
Puncture resistance							
Stress, lbs		25.4	30.6	32.9	67.9	45.0	47.8
Elongation, in		1.16	0.24[c]	0.60	0.41	0.83	0.86
Thickness, mils		31	34	35	39	...	33
Hardness, Durometer points 5 second reading		83A	81A	79A	73A	78A	79A
Exposure conditions[d]		Bu, Im	Bu	PR, Bu, Im, Po	Bu	Im,Po	Im

See footnotes at end of table.

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APPENDIX A (Continued). PROPERTIES[a] OF UNEXPOSED MEMBRANE LINERS

Polymer Liner number[b]	Direction of test	ELPO 36	EPDM 8	EPDM 16/18	EPDM 26	EPDM 41	EPDM 83R	EPDM 91
Analytical properties								
Specific gravity		0.938	1.173	1.122	1.169	0.938	1.199	1.160
Ash (db), %		0.90	6.78	5.42	7.67	0.93	0.32	7.33
Volatiles, %		0.15	0.38	0.50	0.50	0.16	0.31	0.34
Extractables (db), %		5.50	23.41	31.77	22.96	...	18.16	23.64
Physical properties								
Average thickness, mils		23	62	51	39	20	39	37
Tensile at fabric break, ppi	Machine	...	...	...	...	...	43	...
	Transverse	...	...	...	...	...	29	...
Elongation at fabric break, %	Machine	...	...	...	...	...	20	...
	Transverse	...	...	...	...	...	...	...
Tensile strength, psi	Machine	2715	1895	1515	1915	3290	1010	1865
	Transverse	2525	1855	1440	1845	2720	870	1790
Elongation at break, %	Machine	675	565	425	450	700	265	475
	Transverse	655	595	400	475	650	240	500
Tensile set, %	Machine	465	26	13	11	495	59	11
	Transverse	445	24	9	12	438	51	10
S-100, psi	Machine	940	325	355	360	950	890	375
	Transverse	905	285	355	315	920	630	300
S-200, psi	Machine	1035	690	755	940	1060	990	915
	Transverse	1000	615	755	795	1020	845	795
Tear strength (Die C), ppi	Machine	390	230	180	180	430	...	195
	Transverse	375	240	180	185	415	...	195
Puncture resistance								
Stress, lbs		26.3	56.9	39.4	31.3	25.1	33.6	29.2
Elongation, in		0.97	1.46	1.44	1.24	0.96	0.61	1.17
Thickness, mils		24	62	53	...	20	39	...
Hardness, Durometer points 5 second reading		89A	56A	54A	58A	81A	70A	52A
Exposure conditions[d]		Bu,Im,Po	Bu,Im	PR,Bu,Im	Bu	Im	Im	Im

See footnotes at end of table.

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APPENDIX A (Continued). PROPERTIES[a] OF UNEXPOSED MEMBRANE LINERS

Polymer		Neoprene				
Liner number[b]	Direction of test	9	37	42R	82	90
Analytical properties						
Specific gravity		1.503	1.451	1.312	1.480	1.390
Ash, (db)		12.98	3.31	27.70	13.21	4.67
Volatiles, %		0.76	0.64	0.86	0.19	0.37
Extractables (db), %		10.15	...	...	13.43	21.46
Physical properties						
Average thickness, mils		60	73	19	60	37
Tensile at break, ppi	Machine	...	...	331	...	...
	Transverse	...	...	192	...	...
Tensile strength, psi	Machine	2295	2400	...	1835	2185
	Transverse	2090	2330	...	1675	2010
Elongation at break, %	Machine	340	265	25	390	415
	Transverse	340	290	25	410	415
Tensile set, %	Machine	11	2	2	10	26
	Transverse	13	3	2	9	25
S-100, psi	Machine	640	765	...	405	565
	Transverse	560	570	...	360	550
S-200, psi	Machine	1320	1800	...	875	1450
	Transverse	1150	1470	...	705	1225
Tear strength, ppi (Die C)	Machine	220	220	...	180	205
	Transverse	210	200	...	180	195
Puncture resistance						
Stress, lbs		58.7	80.4	124.6	53.9	44.9
Elongation, in		1.16	1.02	0.37	1.29	1.01
Thickness, mils		62	73	19	...	37
Hardness, Durometer points 5 second reading		66A	67A	73A	57A	61A
Exposure conditions[d]		Bu, Im	Im	Im	Bu, Po	Im

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APPENDIX A (Continued). PROPERTIES[a] OF UNEXPOSED MEMBRANE LINERS

Polymer Liner number[b]	Direction of test	Polybutylene 98	Polyester 75	LDPE 21	HDPE 99
Analytical properties					
Specific gravity		0.915	1.236	0.931	0.943
Ash (db), %		0.08	0.38	0.11	...
Volatiles, %		0.12	0.26	0.00	...
Extractables (db), %		...	2.74	...	...
Physical properties					
Average thickness, mils		8	7	10	111
Tensile at yield, ppi	Machine	...	...	...	284
	Transverse	...	...	...	301
Elongation at yield, %	Machine	...	...	...	...
	Transverse	...	...	...	...
Tensile strength, psi	Machine	5625	6770	1700	5110
	Transverse	5580	6765	2590	5330
Elongation at break, %	Machine	390	560	320	1100
	Transverse	375	590	690	1140
Tensile set, %	Machine	245	340	175	...
	Transverse	230	370	565	...
S-100, psi	Machine	2330	2715	1270	1850
	Transverse	2360	2455	1030	1930
S-200, psi	Machine	3035	2880	1470	1855
	Transverse	3200	2585	1050	1920
Tear strength (Die C), ppi	Machine	355	910	415	...
	Transverse	380	780	360	...
Puncture resistance					
Stress, lbs		13.9	29.9	13.9	...
Elongation, in		0.66	1.30	0.76	...
Thickness, mils		8	6.5	10.5	...
Hardness, Durometer points 5 sec reading		94A	93A	97A	94A
Exposure conditions[d]		CB,Bu,Im,Po	Im,Po	PR, Bu, Im, Po,CB,LS	Bu

See footnotes at end of table

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APPENDIX A (Continued). PROPERTIES[a] OF UNEXPOSED MEMBRANE LINERS

Polymer		Polyvinyl chloride						
Liner number[b]		10	11	15	17	19	40	59
	Direction of test							
Analytical properties								
Specific gravity		...	1.275	...	1.264	1.231	1.289	1.280
Ash (db), %		...	6.20	6.30	5.81	3.65	8.09	6.94
Volatiles, %		0.30	0.11	0.47	0.09	0.05	0.21	0.31
Extractables (db), %		32.54	33.90	...	37.25	38.91	...	35.86
Physical properties								
Average thickness, mils		32	30	10	20	22	33	33
Tensile strength, psi	Machine	3400	3135	2360	2640	2780	2935	2505
	Transverse	2840	2780	2630	2520	2260	2640	2365
Elongation at break, %	Machine	285	325	200	270	330	385	370
	Transverse	305	340	300	290	340	400	400
Tensile set, %	Machine	108	97	35	68	97	62	45
	Transverse	130	114	82	77	105	71	60
S-100, psi	Machine	1675	1555	1680	1260	1150	1235	1020
	Transverse	1350	1340	1230	1130	1060	1115	895
S-200, psi	Machine	2615	2295	2360	2080	1890	1825	1570
	Transverse	2075	1950	1880	1850	1590	1610	1355
Tear strength (Die C), ppi	Machine	390	380	295	350	295	350	305
	Transverse	380	370	270	315	275	315	285
Puncture resistance								
Stress, lbs		42.9	37.4	12.8	25.8	24.0	43.1	37.3
Elongation, in		0.62	0.63	0.61	0.69	0.71	0.72	0.78
Thickness, mils		32	32	10	20	21	...	...
Hardness, Durometer points 5 second reading		82A	80A	72A	76A	72A	74A	71A
Exposure conditions[d]		Bu	Bu,Im,Po	Bu	PR,Bu, Im,Po	Bu,Im,Po	Im	Po

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See footnotes at end of table.

APPENDIX A (Continued). PROPERTIES[a] OF UNEXPOSED MEMBRANE LINERS

Polymer		Polyvinyl chloride					PVC+Pitch
Liner number[b]	Direction of test	67	88	89	92A	93	52
Analytical properties							
Specific gravity		1.245	1.255	1.308	...	1.283	1.294
Ash (db), %		5.34	2.80	5.67	5.84	4.94	9.46
Volatiles, %		0.03	0.17	0.03	0.23	0.12	0.39
Extractables (db), %		38.13	33.46	25.17	32.75	32.26	...
Physical properties							
Average thickness, mils		22	20	11	20	11	80
Tensile strength, psi	Machine	3020	3395	3715	2435	3575	1185
	Transverse	2765	2910	3085	2145	3035	1005
Elongation at break, %	Machine	385	325	315	245	325	150
	Transverse	415	335	325	255	350	175
Tensile set, %	Machine	192	102	196	43	98	36
	Transverse	207	101	205	48	117	18
S-100, psi	Machine	1250	1870	1845	1515	1750	1175
	Transverse	1110	1600	1530	1365	1420	860
S-200, psi	Machine	1820	2610	2715	2170	2580	...
	Transverse	1585	2190	2195	1885	2055	...
Tear strength (Die C), ppi	Machine	340	460	410	435	400	290
	Transverse	295	470	390	375	360	210
Puncture resistance							
Stress, lbs		27.8	28.6	17.0	27.4	0.55	62.3
Elongation, in		0.68	0.56	0.48	0.62	15.90	0.49
Thickness, mils		22	...	11	20	...	80
Hardness, Durometer points 5 sec reading		75A	80A	82A	82A	78A	69A
Exposure conditions[d]		Bu,Im	Bu,Im	Im	Bu	Bu,Po	Im

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[a] Analytical properties: specific gravity and ash, ASTM D297; volatiles, percent loss of weight after two hours at 105°C; extractables, Matrecon method (ASTM D3421, modified).
Physical properties: tensile, elongation, modulus, and set, ASTM D412; tear strength, ASTM D624; puncture resistance, FTMS 101B, Method 2065; hardness, ASTM D2240.

[b] Contractor's liner numbers. R = fabric-reinforced.

[c] Elongation at maximum stress.

[d] Exposure conditions:
PR - Primary
Bu - Secondary
Im - Immersion
Po - Pouch test
CB - Collection bag
LS - Liner for simulator

APPENDIX B-1. COMPOSITION AND PROPERTIES OF ADMIXED AND ASPHALT MEMBRANE LINERS - UNEXPOSED AND AFTER EXPOSURE

	Asphalt concrete	Hydraulic asphalt concrete	Soil cement	Soil asphalt
Basic composition	7.1 parts 60-70 pen paving asphalt, 100 parts aggregate	9.0 parts 60-70 pen paving asphalt, 100 parts aggregate	95 parts soil, 5 parts Kaolin clay, 10 parts type 5 cement, 8.8 parts water	7.0 parts SC-800 liquid asphalt, 100 parts aggregate
Thickness, in.	2.2	2.4	4.5	4
Tests of aggregates				
Particle size distribution of aggregate				
Passing 4 mesh, %	90.7	89.4	88.9	79.2
" 8 ", %	61.0	67.1	70.8	55.8
" 16 ", %	45.1	50.9	53.7	39.9
" 30 ", %	30.1	33.7	38.8	27.3
" 50 ", %	19.4	21.5	29.2	18.5
" 100 ", %	11.2	12.4	20.8	13.4
" 200 ", %	6.6	7.2	15.0	11.4
Soil tests				
Sand equivalent	...	...	27	31
Liquid limit	...	...	17.6	17.0
Plastic limit	...	...	Non-plastic	Non-plastic
Plasticity index	...	...	Non-plastic	Non-plastic
Asphalt tests				
Penetration at 25°C/100 g/5 sec				
Before mixing	68	68	...	...
Extracted from core	44	62	...	...
Microductility at 25°C, mm	40	76	...	7
Properties of unexposed samples				
Density, g/cm^3	2.387	2.416	2.169 (dry)[a]	2.228
lb/ft^3	149.0	150.8	135.4 (dry)[a]	139.1
Voids ratio (vol. voids/vol. solids), %	6.4	2.9	...	10.4
Water swell, mil	1	0	0	17
Coefficient of permeability, cm sec^{-1}	1.2×10^{-8}	3.3×10^{-9}	1.5×10^{-6}[a]	1.7×10^{-3}
Compressive strength				
Initial, psi	2805	2710	1910[a]	1220
After 24 h immersion in water[b], psi	2230	2330	1320[a]	185
Retention of strength after immersion, %	80	86	69[a]	15

See footnotes at end of table.

APPENDIX B-1 (Continued). COMPOSITION AND PROPERTIES OF ADMIXED AND ASPHALT MEMBRANE LINERS - UNEXPOSED AND AFTER EXPOSURE

	Asphalt concrete	Hydraulic asphalt concrete	Soil cement	Soil asphalt
Basic composition	7.1 parts 60-70 pen paving asphalt, 100 parts per aggregate	9.0 parts 60-70 pen paving asphalt, 100 parts per aggregate	95 parts soil, 5 parts Kaolin clay, 10 parts type 5 cement, 8.8 parts water	7.0 parts SC-800 liquid asphalt, 100 parts aggregate
Properties after 12 months of exposure[c]				
Density, as received, g/cm^3	2.430	2.400	...	2.161
Density, dry, g/cm^3	2.400	2.309	...	1.973
Voids ratio as received, %	3.2	1.5	...	15.2
Voids ratio, dry, % (number of samples)	4.2 (3)	1.9 (4)	...	26.1 (3)
Water content, g water per 100 g dry solids (number of samples)	1.00 (3)	0.45 (4)	...	9.6 (3)
Water soluble solids extracted, % (number of samples)	0.008 (1)	<0.01 (2)	...	0.14 (3)
Compressive strength, psi	423	349	1188	15
Percent of original	15	13	62	1.2
Coefficient of permeability, cm sec^{-1} (two samples)	7.4×10^{-7} 9.3×10^{-9}	3.5×10^{-9} $<3 \times 10^{-10}$	1.5×10^{-8} (T)[d] 4.0×10^{-7} (B)	1.3×10^{-8} 2.8×10^{-8}
Properties after 56 months of exposure[c]				
Density, as received, g/cm^3	2.542	2.471	...	2.307
Density, dry, g/cm^3	2.417	2.385	...	2.019
Voids ratio, as received, %	4.3	4.6	...	5.0
Voids ratio, dry, % (number of samples)	5.3 (2)	3.6 (2)	...	14.3
Water content, g water per 100 g dry solids	1.06	0.96	...	6.51
Water soluble solids extracted, % (number of samples)	0.016 (2)	0.008 (2)	...	0.10 (2)
Compressive strength, psi (number of samples)	258 (2)	172 (2)	1182 (4)	26 (2)
Percent of original	9	6	62	2
Coefficient of permeability, cm sec^{-1}	$<10^{-7}$	$<10^{-9}$	1.2×10^{-5} (T)[d] 2.7×10^{-5} (B) 4.3×10^{-7} (T) 1.2×10^{-5} (B)	8.6×10^{-8} (T)[d] 2.7×10^{-7} (B)

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[a] Measured on specimen molded according to ASTM D 558. Wet density, 2.345 g cm^{-3} (146.4 lb ft^{-3}).

[b] Asphalt concrete and hydraulic asphalt concrete immersed in water at 60°C; soil cement and soil asphalt immersed at room temperature.

[c] Measured on 2-inch cores cut from liner specimens.

[d] Data for top (T) and bottom (B) of core are shown.

APPENDIX B-2. PROPERTIES OF ASPHALT IN ADMIX MATERIALS AND MEMBRANES AFTER 12, 43, AND 56 MONTHS OF EXPOSURE TO MSW LANDFILL LEACHATE

	Paving asphalt concrete			Hydraulic asphalt concrete			Soil asphalt			Bituminous seal	Asphalt on non-woven fabric
	Whole core	Top	Bottom	Whole core	Top	Bottom	Whole core	Top	Bottom		
Type of asphalt	60-70 pen paving grade asphalt			60-70 pen paving grade asphalt			Slow curing liquid asphalt, SC-800 grade			Catalytically blown asphalt	Emulsified asphalt
Viscosity at 25°C in sliding plate viscometer at shear rate of 0.05 sec^{-1}:											
Original, MP	5.1[a]	...	...	2.1[a]	...	...	0.02[b]	...	...	8.5	4.5[b]
After 12 months, MP	8.8	...	...	3.3	...	...	0.04	...	...	10.4	2.9
After 43 months, MP	...	...	...	...	...	...	...	...	...	12.2	3.1
After 56 months, MP	9.9	9.1	10.7	9.9	4.2	13.5	0.01	0.005	0.012	17.4	3.1
Change from original, MP	+4.8	+4.0	+5.6	+7.8	+2.1	+11.4	-0.01	-0.015	-0.008	+8.9	-1.4
Penetration at 25°C at 100 g/5 sec:											
Original	44[d]	...	...	62[d]	...	...	538[b,e]	...	...	36[e]	46[b,e]
After 12 months[e]	36	...	...	52	...	...	390	...	...	34	55
After 43 months[e]	...	...	...	...	...	...	...	...	...	31	53
After 56 months[e]	34	35	33	39	47	30	844	1020	668	27	53
Change from original	-10	-9	-11	-23	-15	-32	+306	+482	+130	-9	+7
Voids ratio (volume voids/volume solids x 100):											
Original	5.4	...	...	2.9	...	...	10.4	...	...	...	...
Wet after 12 months	3.2	...	...	1.5	...	...	15.2	...	...	...	...
Wet after 56 months	4.3	...	...	4.6	...	...	5.0	...	...	...	...
Dry after 12 months	4.2	...	...	1.9	...	...	26.1	...	...	...	...
Dry after 56 months	5.3	...	...	3.6	...	...	14.3	...	...	...	...
Softening point, °C:											
Original	...	...	...	...	...	...	...	...	...	89	...
After 12 months	...	...	...	...	...	...	...	...	...	89	...
After 56 months	...	...	...	...	...	...	...	...	...	101	...

[a] Calculated from penetration data.
[b] Asphalt extracted from unexposed specimens stored 12 months.
[d] Asphalt before mixing was 68 penetration, i.e., ca. 1.7 MP.
[e] Calculated from viscosity data.

APPENDIX C-1. ANALYSES OF LEACHATES GENERATED BY LANDFILL SIMULATORS AFTER 11 MONTHS OF OPERATION[a]

Simulator	Solids content, %				Volatile acids, g/L			
number	Total	Volatile	pH	COD	Acetic	Propionic	Isobutyric	Butyric
1	5.68	3.63	5.05	36.5	9.5	2.8	0.9	6.6
2	5.92	3.78	5.05	50.6	10.1	2.8	0.7	7.2
3	6.29	3.96	5.10	46.9	7.2	2.2	0.6	6.3
4	5.25	3.29	5.05	43.7	10.0	2.7	0.6	7.0
5	5.52	3.36	5.05	54.1	8.9	2.9	0.6	6.8
6	5.07	3.36	5.07	48.5	7.4	2.5	0.6	5.6
7	5.57	3.71	5.07	48.5	4.5	2.4	0.9	6.4
8	4.87	2.71	5.05	48.5	6.1	2.5	0.3	6.4
9	5.63	3.34	5.10	47.1	5.7	2.6	0.7	6.3
10	5.53	3.30	5.05	48.5	10.9	3.7	0.9	8.2
11	5.75	3.44	5.10	51.4	6.7	2.2	0.8	7.2
12	5.20	3.04	5.05	47.8	3.9	2.4	0.7	5.9
13	5.23	3.09	5.05	46.9	3.7	1.7	0.5	4.3
14	3.99	2.33	5.05	36.3	3.8	2.0	0.5	5.0
15	5.59	3.36	5.15	47.1	3.5	1.7	0.7	4.1
16	4.93	2.80	5.07	52.4	5.8	2.4	0.5	6.1
17	6.45	4.18	5.07	49.6	5.7	1.7	0.4	7.1
18	6.11	3.75	5.05	56.2	5.2	2.5	0.5	7.3
19	5.52	3.72	5.03	50.3	5.4	2.7	0.5	7.0
20	4.69	2.62	5.05	50.0	4.7	2.4	0.4	5.5
21	4.92	2.96	5.05	27.9	4.1	2.2	0.2	5.1
22	4.81	2.78	5.00	40.8	5.3	2.5	0.4	5.8
23	5.53	3.44	5.07	42.3	5.2	2.4	0.6	5.3
24	5.34	3.18	5.07	44.7	5.0	2.4	0.6	6.0
Average	5.39	3.30	5.06	46.5	6.2	2.4	0.6	6.2

[a] Leachate collected on October 15, 1975

APPENDIX C-2

ANALYSES OF LEACHATES GENERATED BY LANDFILL SIMULATORS AFTER 54 MONTHS OF OPERATION[a]

Simulator number	Solids content, %		pH	COD, g/L	TVA,[b] g/L
	Total	Volatile			
1	0.21	0.06	7.19	0.6	1.2
2	0.14	0.09	8.65	2.1	3.0
3	0.18	0.04	7.21	0.5	0.9
4	0.23	0.14	7.57	0.5	1.0
5	0.61	0.35	6.85	8.4	4.5
6	0.16	0.05	7.42	0.5	1.3
7	0.76	0.45	6.10	7.7	5.9
8	0.23	0.10	7.18	2.5	1.4
9	0.79	0.52	6.79	9.7	4.2
10	0.74	0.40	6.36	10.9	4.8
11	0.16	0.12	8.15	1.4	1.0
12	0.44	0.20	5.92	6.0	3.6
Average	0.39	0.21	7.12	4.3	2.7

[a] Leachate collected on May 1, 1979. Urea, 113 g, had been added every two weeks since November 6, 1978 to all the simulators, except Numbers 2 and 10. Number 2 received 226 g every two weeks and Number 10 received 113 g on Nov. 6, 1978 only.

[b] Total volatile acids, as acetic acid.

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APPENDIX D. PROPERTIES OF PRIMARY POLYMERIC MEMBRANE LINER SPECIMENS BEFORE AND AFTER EXPOSURE TO LEACHATE

Length of exposure, days		0	365	1708	0	365	1708
Polymer		Butyl	Butyl	Butyl	CPE	CPE	CPE
Liner number		7	7	7	12	12	12
	Direction of test						
Analytical properties							
Specific gravity		1.206	...	...	1.360	...	...
Ash (db), %		5.25	...	...	14.40	...	...
Volatiles, %		0.45	2.02	2.37	0.10	6.84	7.61
Extractables (db), %		10.96	...	9.76	7.47	...	5.09
Physical properties							
Average thickness, mils		63	64	64	31	35	37
Tensile strength, psi	Machine	1445	1345	1490	2465	2085	2270
	Transverse	1425	1405	1440	2085	1530	1650
Elongation at break, %	Machine	365	425	420	305	350	360
	Transverse	430	390	385	515	450	410
Tensile set, %	Machine	15	13	12	199	208	160
	Transverse	19	14	11	231	207	160
S-100, psi	Machine	355	270	320	1220	1025	1060
	Transverse	290	320	350	520	460	510
S-100, ppi	Machine	...	...	...	38.4	...	...
	Transverse	...	...	...	16.4	...	...
S-200, psi	Machine	775	630	720	1815	1450	1460
	Transverse	615	740	780	840	730	820
S-200, ppi	Machine	...	...	...	56.4	...	...
	Transverse	...	...	...	26.0	...	...
Tear strength (Die C), lb	Machine	11.3	12.6	12.1	8.3	12.8	6.8
	Transverse	11.3	12.9	11.9	7.4	8.9	5.9
Puncture resistance:							
Thickness, mils		65	64	64	32	35	37
Stress, lb		44.8	49.5	50.0	47.0	49.8	51.8
Elongation, in.		1.22	1.20	1.25	1.04	0.98	.98
Hardness, Durometer points		51A	51A	51A	77A	66A	70A

Continued

APPENDIX D (Continued). PROPERTIES OF PRIMARY POLYMERIC MEMBRANE LINER SPECIMENS
BEFORE AND AFTER EXPOSURE TO LEACHATE

Length of exposure, days		0	365	1708	0	365	1708
Polymer		CSPE	CSPE	CSPE	EPDM	EPDM	EPDM
Liner number		6R	6R	6R	18	18	18
	Direction of test						
Analytical properties							
Specific gravity		1.343	...	...	1.122	...	...
Ash (db), %		3.28	...	...	5.42	...	...
Volatiles, %		0.51	12.76	13.90	0.50	5.54	5.74
Extractables (db), %		3.77	...	3.35	31.77	...	28.27
Physical properties							
Average thickness, mils		31	38	37	49	51	49
Tensile of fabric at break, ppi	Machine	36.0	28.0	37.0	...	...	...
	Transverse	33.9	33.9	35.0	...	...	...
Elongation of fabric at break, %	Machine	30	...	...	...	...	...
	Transverse	15	...	...	...	...	...
Tensile strength, psi	Machine	1915	1785	2330	1515	1445	1520
	Transverse	1610	1500	1890	1440	1460	1360
Elongation at break, %	Machine	250	300	245	425	435	380
	Transverse	245	300	220	400	440	370
Tensile set, %	Machine	119	105	65	13	12	5
	Transverse	106	106	50	9	12	7
S-100, psi	Machine	1005	710	845	355	320	350
	Transverse	855	475	800	355	300	305
S-100, ppi	Machine	30.8	...	...	17.2	...	...
	Transverse	27.2	...	...	17.2	...	...
S-200, psi	Machine	1710	1455	1980	755	775	860
	Transverse	1335	1035	1670	755	710	735
S-200, ppi	Machine	53.1	...	...	37.2	...	...
	Transverse	43.0	...	...	37.2	...	...
Tear strength (Die C), lb	Machine	9.8	10.7	8.0	8.9	9.8	6.6
	Transverse	8.9	12.3	6.7	8.9	9.7	7.1
Puncture resistance:							
Thickness, mils		35	38	37	53	51	49
Stress, lb		32.9	57.0	58.2	39.4	40.1	41.5
Elongation, in.		0.60	0.88	0.86	1.44	1.18	1.19
Hardness, Durometer points		77A	64A	70A	54A	52A	51A

Continued

APPENDIX D (Continued). PROPERTIES OF PRIMARY POLYMERIC MEMBRANE LINER SPECIMENS BEFORE AND AFTER EXPOSURE TO LEACHATE

Length of exposure, days		0	365	1708	0	365	1708
Polymer		LDPE	LDPE	LDPE	PVC	PVC	PVC
Liner number		21	21	21	17	17	17
	Direction of test						
Analytical properties							
Specific gravity		...	...	...	1.264	...	...
Ash (db), %		...	...	...	5.81	...	...
Volatiles, %		ca. 0	0.02	1.95	0.09	3.55	2.08
Extractables (db), %		...	...	3.37	37.25	...	34.39
Physical properties							
Average thickness, mils		11	11	10	20	21	22
Tensile strength, psi	Machine	1700	2475	2610	2640	2480	2920
	Transverse	2590	2460	2560	2520	2190	2560
Elongation at break, %	Machine	320	490	470	270	320	340
	Transverse	690	625	610	290	340	335
Tensile set, %	Machine	175	365	350	68	55	55
	Transverse	565	500	470	77	59	68
S-100, psi	Machine	1270	1210	1390	1260	1180	1530
	Transverse	1030	1010	1050	1130	975	1130
S-100, ppi	Machine	...	...	...	25.2	...	...
	Transverse	...	...	...	22.6	...	...
S-200, psi	Machine	1470	1360	1500	2080	1685	1940
	Transverse	1050	1050	1150	1850	1425	1680
S-200, ppi	Machine	...	...	...	41.6	...	...
	Transverse	...	...	...	37.0	...	...
Tear strength (Die C), lb	Machine	4.2	5.7	4.4	7.0	11.3	6.5
	Transverse	3.6	5.2	3.6	6.3	9.4	6.0
Puncture resistance:							
Thickness, mils		11	11	10	20	21	22
Stress, lb		13.9	14.8	17.1	25.8	30.1	31.3
Elongation, in.		0.76	0.80	1.24	0.69	0.70	0.84
Hardness, Durometer points		97A	...	...	76A	64A	70A

APPENDIX E. PROPERTIES OF BURIED POLYMERIC MEMBRANE SPECIMENS AFTER 12 MONTHS EXPOSURE TO LEACHATE GENERATED IN SIMULATED MSW LANDFILLS

Material	Asphalt fiberglass roofing	Butyl rubber			Chlorinated polyethylene					
Specimen number[a]	5	7	22	24	12-1	12-2	12-3	12-4	13R-1	13R-2
Type of compound[b]	-	XL	XL	XL	TP	TP	TP	TP	TP	TP
Simulator number	21	21	21	21	22	22	22	22	24	24
Nominal thickness, mils	69-75	62.5	75	99	32	32	32	32	36	36
Analytical properties										
Volatiles, %	...	1.5	2.3	1.0	9.4	9.5	10.2	9.0	12.8	11.4
Physical properties[c]										
Tensile at fabric break, ppi	...	...	...	...	...	...	...	...	127.2	132.8
Tensile at break, psi	...	1360	1300	1470	2000	1940	2005	1840	1020	975
Elongation at break, %	...	450	575	425	375	350	350	325	150	175
Set after break, %	...	17	65	7	200	180	185	180	81	77
S-100, psi	...	270	320	340	990	990	980	980	930	930
S-200, psi	...	600	480	720	1380	1380	1420	1405	...	...
S-300, psi	...	940	620	1120	1780	1780	1830	1830	...	...
Tear strength (Die C), ppi	...	210	170	205	260	305	245	265	...	...
Hardness, Durometer points, 10 sec. reading	59A	44A	52A	55A	66A	67A	66A	69A	58A	59A
Puncture strength:										
Thickness of specimen, mils	72	65	75	96	...	36	35	36	40	40
Stress, lb	4.8	41.0	43.2	58.2	...	42.0	44.0	45.0	59.0	61.0
Elongation, in.	0.16	1.08	1.16	1.08	...	0.76	0.94	0.98	0.40	0.42
Seam strength										
Bonding system	...	XL-ADH[d] 8800 w/tape	XL-ADH[d] 8800 w/tape	XL-ADH[d] 8800 w/tape	Cement SC-1556	Solvent 50 Toluene 50 THF[e]	Solvent 60 Tri-chloroethane 40 Toluene	Cement SC-1554	Cement SC-1556	Solvent 50 Toluene 50 THF[f]
Shear, ppi:	...	37.3	27.3	37.2	46.0	56.0	51.0	48.1	>122	>58
Locus of failure[f]	...	AD-LS	AD-LS	AD-LS	AD-LS	LS	LS	AD-LS	BK	OR
Peel:										
Average, ppi	...	3.7	5.1	2.8	2.2	2.4	3.0	8.3	3.8	2.5
Maximum, ppi	...	4.0	7.2	3.4	3.7	3.1	4.4	11.6	5.2	3.7
Locus of failure[f]	...	AD-LS	AD	AD-LS	AD-LS	LS	LS	AD	AD-LS	LS

See footnotes at end of table.

APPENDIX E (Continued). PROPERTIES OF BURIED POLYMERIC MEMBRANE SPECIMENS AFTER 12 MONTHS EXPOSURE TO LEACHATE GENERATED IN SIMULATED MSW LANDFILLS

Material	Chlorinated polyethylene						Chlorosulfonated polyethylene		
Specimen number[a]	13R-3	13R-4	23-1	23-2	23-3	23-4	3-1	3-2	4R-1
Type of compound[b]	TP	TP	TP	TP	TP	TP	TP	TP	TP
Simulator number	24	24	23	23	23	23	20	20	20
Nominal thickness, mils	30	30	14	14	14	14	31	31	33
Analytical properties									
Volatiles, %	12.2	13.1	11.3	10.8	10.9	8.4	21.1	18.8	18.7
Physical properties[d]									
Tensile at fabric break, ppi	82.4	132.0	...	...	...	...	...	...	33[g]
Tensile at break, psi	1025	1115	2360	2290	2180	2040	1415	1440	920[g]
Elongation at break, %	150	150	325	300	300	300	675	675	625[g]
Tensile set, %	74	68	180	175	170	170	295	295	265[g]
S-100, psi	980	1060	1670	1640	1240	1160	200	280	240[g]
S-200, psi	...	...	2220	2200	1730	1600	260	380	290[g]
S-300, psi	...	...	2360	2290	2180	2040	320	450	340[g]
Tear strength (Die C), ppi	...	...	335	305	300	355	160	170	...
Hardness, Durometer points, 10 sec. reading	57A	59A	69A	71A	70A	71A	61A	62A	69A
Puncture strength:									
Thickness of specimen, mil	41	41	18	18	18	19	37	37	42
Stress, lb	60.5	60.0	23.0	23.6	24.2	24.6	29.0	30.0	25.9
Elongation, in.	0.34	0.38	0.82	0.84	0.82	0.84	1.62	1.62	0.76
Seam strength									
Bonding system	Solvent 60 Tri-chloroethane 40 Toluene	Cement SC-1554	Cement SC-1556	Solvent 50 Toluene 50 THF[e]	Solvent 60 Tri-chloroethane 40 Toluene	Cement SC-1554	Heat Factory	Solvent 6079+ Cement L1552	Heat Factory
Shear, ppi:	43	>58	...	>31	>33	>34	...	18.0	>26
Locus of failure[f]	LS	BK	...	BK	BK	BK	...	AD	BK
Peel:									
Average, ppi	1.2	5.8	1.0	4.8	2.7	5.4	...	2.6	(h)
Maximum, ppi	1.9	5.9	1.7	6.6	3.2	6.6	...	3.6	>21
Locus of failure[f]	LS	AD-LS	AD-LS	LS	LS	AD-LS	...	AD	RIP

See footnotes at end of table.

APPENDIX E (Continued). PROPERTIES OF BURIED POLYMERIC MEMBRANE SPECIMENS AFTER 12 MONTHS EXPOSURE TO LEACHATE GENERATED IN SIMULATED MSW LANDFILLS

Material	Chlorosulfonated polyethylene			Ethylene propylene rubber				Natural rubber	Neoprene	Neoprene gasket	
										Solid	Sponge
Specimen number[a]	4R-2	6R	14R	8	16	25	26	30	9	33	34
Type of compound[b]	TP	TP	TP	XL	XL	XL	XL	XL	XL	XL	XL
Simulator number	20	22	21	17	23	24	18	13	20	14	13
Nominal thickness, mils	33	34	32-39	62.5	53	60	30	125	62.5	125-137	250
Analytical properties											
Volatiles, %	19.3	14.5	8.7	6.0	5.5	5.6	9.0	...	8.7	...	...
Physical properties[d]											
Tensile at fabric break, ppi	45[g]	34.2	120	...	..	...	...	...	...	...	...
Tensile at break, psi	960[g]	1860	1230	1780	1140	1610	1660	1275	1620	1005	100
Elongation at break, %	600[g]	275	150	575	475	525	425	650	350	575	250
Set after break, %	265[g]	94	26	25	11	22	7	6	2	11	58
S-100, psi	260[g]	690	1140	300	240	390	340	100	340	85	50
S-200, psi	295[g]	1470	...	720	530	820	820	150	905	170	85
S-300, psi	340[g]	...	...	1130	780	1160	1290	210	1470	270	...
Tear strength (Die C), ppi	...	...	...	240	195	235	175	...	180	...	...
Hardness, Durometer points, 10 sec. reading	67A	69A	63A	55A	49A	60A	54A	35A	57A	31A	...
Puncture strength:											
Thickness of specimen, mils	41	40	40	65	58	66	35	...	72	...	...
Stress, lb	27.0	46.0	45.6	53.6	42.1	45.3	26.3	...	55.9	...	...
Elongation, in.	0.70	0.64	0.54	1.18	1.16	1.10	1.04	...	1.12	...	...
Seam strength											
Bonding system	Solvent 6079+ Cement L-1552	Cement 280Z	Solvent Trichloroethylene	XL-ADH[d] 8800 w/tape	Solvent 374 Cement Mag 1265	XL-ADH[d] 8800 w/tape	XL-ADH[d] 8800 w/tape	No seam	Cement N-100	No seam	No seam
Shear, ppi:	0	>64	16.0	45.0	16.0	42.3	41.3	...	62.3	...	...
Locus of failure[g]	AD	BK	LS	AD	AD-LS	AD-LS	AD	...	AD-LS	...	...
Peel:											
Average, ppi	0	17	0.6	7.3	2.1	8.0	5.6	...	4.9	...	...
Maximum, ppi	0	26	1.3	7.4	2.4	8.7	6.1	...	6.3	...	...
Locus of failure[g]	AD	AD	LS	AD	AD-LS	AD-LS	AD	...	AD-LS	...	...

See footnotes at end of table.

APPENDIX E (Continued). PROPERTIES OF BURIED POLYMERIC MEMBRANE SPECIMENS AFTER 12 MONTHS EXPOSURE TO LEACHATE GENERATED IN SIMULATED MSW LANDFILLS

Material	Polybutylene	Polypropylene	Polyvinyl chloride						SBR[i]	Urethane rubber
Specimen number[a]	20	27	10	11	15	17	19-1	19-2	31	32
Type of compound[b]	CX	CX	TP	TP	TP	TP	TP	TP	XL	XL
Simulator number	19	14	19	19	19	19	19	19	13	13
Nominal thickness, mils	8-10	10	34	31	10	20	20	20	125	47-62
Analytical properties										
Volatiles	0.3	0.4	6.7	5.0	4.6	3.3	1.2	0.4	..	...
Physical properties[c]										
Tensile at break, %	5330	6560	2550	2780	2000	2660	2745	2860	820	1390
Elongation at break, %	350	825	325	400	225	350	400	400	200	550
Set after break, %	220	595	73	98	26	64	87	87	12	19
S-100, psi	2220	3040	1230	1220	1490	1200	1270	1295	525	445
S-200, psi	3070	3120	1770	1740	1960	1700	1745	1790	820	515
S-300, psi	4440	3200	2320	2260	...	2360	2220	2320	...	635
Tear strength (Die C), ppi	800	960	510	430	460	385	400	385	...	...
Hardness, Durometer points 10 sec. reading	...	...	73	76A	73A	72A	71A	72A	70A	77A
Puncture strength:										
Thickness of specimen, mils	10	10	34	31	11	20	22	21	...	...
Stress, lb	21.2	20.5	41.5	45.1	36.0	24.0	29.8	28.8	...	...
Elongation, in.	0.64	0.68	0.52	0.64	0.62	0.66	0.82	0.82	...	...
Seam strength:										
Bonding system	Heat Laboratory	No seam	Solvent THF[e]	Solvent THF[e]	Cement L1552+ Solvent 6079	Cement L1552+ Solvent 6079	Cement L1552+ Solvent 6079	Solvent THF[e]	No seam	No seam
Shear, ppi:	...	...	>82	>65	>9.5	>31	>36	...	...	...
Locus of failure[f]	...	...	BK	BK	BK	BK	BK	...	...	...
Peel:										
Average, ppi	(h)	...	10.4	10.2	2.1	2.2	4.9	3.0	...	...
Maximum, ppi	11.8	...	14.3	14.3	2.6	2.9	6.0	6.5	...	...
Locus of failure[f]	LS	...	LS	LS	AD	AD	AD	LS	...	...

[a] Contractor's identification number. R = fabric reinforced.

[b] XL = Crosslinked or vulcanized; TP = thermoplastic; CX = partially crystalline thermoplastic.

[c] Tensile and tear properties measured in machine direction, except where otherwise noted.

[d] Vulcanized adhesive.

[e] THF = tetrahydrofuran.

[f] Locus of failure code.

AD = Failure within adhesive.
AD-AD = Failure between two coats of adhesive.
AD-LS = Failure between adhesive and liner surface.
BK = Break of liner materials outside the seam.
CL = Failure in clamped area.
DEL = Delamination of the liner material.
LS = Failure at liner surface.
OR = Failure of reinforcing fabric.
RIP = Rip outside of seam test area.
SE = Failure at seam edge.

The use of a slash indicates that the two specimens failed in different ways.

[g] Tested in transverse direction.

[h] Spec men failed at initial peak.

[i] SBR = Styrene butadiene rubber gasket compound.

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APPENDIX F. PROPERTIES OF BURIED POLYMERIC MEMBRANE SPECIMENS AFTER 43 MONTHS OF EXPOSURE TO LEACHATE IN SIMULATORS #11 AND #12

Material[a]		EPDM		PVC		Polypropylene	TPR		Natural rubber	SBR	Urethane rubber	Neoprene gasket	
												Solid	Sponge
Specimen number[b]		8	26	15	17	27	28	29	30	31	32	33	34
Type of compound[c]		XL	XL	TP	TP	CX	TP	TP	XL	XL	XL	XL	XL
Simulator number		11	12	11	11	11	11	12	12	12	12	11	12
Nominal thickness, mils		62.5	30	10	20	10	71-76	67-76	125	125	47-62	125-237	250
	Direction of test												
Analytical properties													
Volatiles[d], %		4.23	8.08	1.40	1.30	0.19	7.34	3.65	5.79	7.65	1.53	12.54	54.30
Physical properties													
Thickness, avg. 3 readings, mils		66.0	35.5	11.0	20.0	10.5	30.0	73.5	166.0	149.5	61.5	116.0	183.5
Tensile at break, psi		1780	1620	2180	2760	6040	290[e]	1030	2200	820	370	550	140
Elongation at break, %	Machine	550	400	280	380	650	300	300	700	200	100	450	280
Set after break, %	Machine	21	18	32	65	320	14	62	10	10	2	5	40
S-100, psi	Machine	565	345	1455	1280	3240	160	810	105	465	375	80	50
S-200, psi	Machine	775	855	2000	1800	3440	225	945	165	820	...	160	105
S-300, psi	Machine	1200	1320	...	2380	3440	295	1030	245	...	...	260	...
Tear strength (Die C), ppi		205	185	380	385	1020	85	245	150	95	100	85	20
Hardness, Durometer points, 10 sec. reading		55A	54A	69A	72A	90A	41A	86A	36A	62A	57A	27A	5A
Puncture strength:													
Thickness of specimens, mils		65	36	11	20	9.5	...	78	156	149	56	165	...
Stress, lb		58	29.6	15.4	29.6	19.2	...	51.4	47.5	59.2	14.0	42.0	...
Elongation, in.		1.44	1.28	0.70	0.88	0.68	...	0.76	1.54	0.68	0.42	1.64	...
Seam strength													
Bonding system		(f)	(f)	(g)	(g)	...	...	...	...	...	...	...	...
Shear, ppi		60.0	23.4	>18.2	>35.2	...	...	...	...	...	...	...	...
Locus of failure[h]		AD-LS	AD-LS	CL	CL	...	...	...	...	...	...	...	...
Peel:													
Average, ppi		8.6	7.4	3.0	3.8	...	...	...	...	...	...	...	...
Maximum, ppi		9.2	8.4	3.8	5.0	...	...	...	...	...	...	...	...
Locus of failure[h]		AD	AD	AD	AD	...	...	...	...	...	...	...	...

[a] TPR = Thermoplastic rubber, molded in laboratory; SBR = styrene-butadiene rubber.

[b] Contractor's identification number.

[c] XL = Crosslinked or vulcanized; TP = thermoplastic; CX = partially crystalline thermoplastic.

[d] Determined by exposing specimens seven days at RT, followed by two hours heating in oven at 105-110°C.

[e] Broke at surface irregularity.

[f] Made in laboratory with 8800 splicing cement + cold seal tape.

[g] Made in factory with Solvent 6079+Cement L1552.

[h] Locus of failure:
AD = Failure within adhesive.
AD-LS = Failure between adhesive and liner surface.
CL = Failure at clamp.

APPENDIX G. PROPERTIES OF BURIED POLYMERIC MEMBRANE SPECIMENS AFTER EXPOSURE TO LEACHATE GENERATED IN SIMULATED MSW LANDFILLS

Material	Asphalt fiberglass roofing	Butyl rubber			Chlorinated polyethylene					
Specimen number^a	5	7	22	24	12-1	12-2	12-3	12-4	13R-1	13R-2
Type of compound^b	-	XL	XL	XL	TP	TP	TP	TP	TP	TP
Simulator number	3	3	3	3	4	4	4	4	6	6
Nominal thickness, mils	69-75	62.5	75	99	32	32	32	32	36	36
Exposure time, months	56	56	56	56	56	56	56	56	56	56
Analytical properties										
Volatiles, %	15.5	2.0	6.1	1.5	10.6	9.8	9.9	...	17.9	...
Extractables, %	...	9.79	24.47	9.15	4.48	8.17	4.53	4.54	3.30	3.91
Solvent	...	MEK^c	MEK^c	MEK^c	n-heptane	n-heptane	n-heptane	n-heptane	n-heptane	n-heptane
Physical properties^d										
Tensile at fabric break, ppi	...	...	...	...	...	...	...	...	59.6	...
Tensile at break, psi	...	1510	1360	1720	2330	2020	2260	...	1065	...
Elongation at break, %	...	435	565	415	305	280	305	...	175	...
Set after break, %	...	16	60	16	180	150	165	...	60	...
S-100, psi	...	300	320	380	1720	1120	1160	...	1015	...
S-200, psi	...	680	495	840	1715	1620	1660	...	...	...
S-300, psi	...	1090	690	1320	2290	2080	2180	...	...	...
Tear strength (Die C), ppi	...	185	160	215	215	210	215	...	...	...
Hardness, Durometer points, 10 sec. reading	...	53A	54A	65A	63A	63A	65A	...	58A	...
Puncture strength:										
Thickness of specimen, mils	84-92	66	77	97	39	39	38	...	42	...
Stress, lb	6.0	38.0	42.0	59.0	48.1	51.1	48.7	...	57.0	...
Elongation, in.	0.18	1.14	1.32	1.20	0.98	0.96	0.96	...	0.48	...
Seam strength										
Bonding system	...	XL-ADH^e 8800 w/tape	XL-ADH^e 8800 w/tape	XL-ADH^e 8800 w/tape	Cement SC-1556	Solvent 50 Toluene 50 THF^f	Solvent 60 Tri-chloroethane 40 Toluene	Cement SC-1554	Cement SC-1556	Solvent 50 Toluene 50 THF^f
Shear, ppi:	...	39.5	34.3	46.1	34.0	...	39.5	57.5	55.8	64.4
Locus of failure^g	...	AD-LS	AD	AD	AD	...	LS	SE	AD-LS	DEL
Peel:										
Average, ppi	...	3.0	8.4	4.8	1.4	2.0	1.8	10.0	0.4	4.0
Maximum, ppi	...	4.2	9.1	6.8	2.6	2.6	2.5	11.7	0.8	4.4
Locus of failure^g	...	AD-LS	AD	AD	AD-LS	LS	LS	AD	AD-LS	LS

See footnotes at end of table.

APPENDIX G (Continued). PROPERTIES OF BURIED POLYMERIC MEMBRANE SPECIMENS AFTER EXPOSURE TO LEACHATE GENERATED IN SIMULATED MSW LANDFILLS

Material	Chlorinated polyethylene							Chlorosulfonated polyethylene		
Specimen number[a]	13R-3	13R-4	23-1	23-2	23-3	23-4	38	3-1	3-2	4R-1
Type of compound[b]	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP
Simulator number	6	6	5	5	5	5	12	2	2	2
Nominal thickness, mils	30	30	14	14	14	14	32	31	31	31
Exposure time, months	56	56	56	56	56	56	13	56	56	56
Analytical properties										
Volatiles, %	18.0	...	13.7	...	13.2	...	7.9	14.7	...	12.9
Extractables, %	4.73	4.60	5.45	5.95	5.68	5.32	8.50	2.27	2.53	2.25
Solvent	n-heptane	n-heptane	n-heptane	n-heptane	n-heptane	n-heptane	n-heptane	DMK[h]	DMK[h]	DMK[h]
Physical properties[d]										
Tensile at fabric break, ppi	64	...	...	...	...	...	...	...	...	46[i]
Tensile at break, psi	1060	...	2240	...	2230	...	1830	...	1870	1042[i]
Elongation at break, %	140	...	290	..	300	...	290	...	590	560[i]
Tensile set, %	56	...	170	...	140	...	165	...	255	230[i]
S-100, psi	1015	...	1250	...	1200	...	1180	...	400	310[i]
S-200, psi	...	...	1720	...	1680	...	1480	...	510	360[i]
S-300, psi	...	...	...	...	...	...	...	...	645	420[i]
Tear strength (Die C), ppi	...	...	250	...	235	...	240	...	185	...
Hardness, Durometer points, 10 sec. reading	60A	...	70A	...	69A	...	...	...	69A	70A
Puncture strength:										
Thickness of specimen, mils	42	...	18	...	18	...	37	...	33	39
Stress, lb	52.4	...	27.8	...	29.0	...	51.9	...	33.5	33.0
Elongation, in.	0.46	...	0.88	...	0.92	...	0.96	...	0.94	0.96
Seam strength										
Bonding system	Solvent 60 Tri-chloroethane 40 Toluene	Cement SC-1554	Cement SC-1556	Solvent 50 Toluene 50 THF[f]	Solvent 60 Tri-chloroethane 40 Toluene	Cement SC-1554	Heat Laboratory	Heat Factory	Solvent 6079+ Cement L1552	Heat Factory
Shear, ppi:	48	78	16	>23	>21	>23	20	32	...	48/30
Locus of failure[g]	LS	DEL	AD-LS	CL	CL	CL	LS	SE	...	OR/RIP
Peel:										
Average, ppi	1.2	4.8	0.4	4.6	2.6	5.4	(j)	11.1	2.3	16.8
Maximum, ppi	1.9	7.3	0.6	5.3	3.0	6.6	5.4	13.3	3.9	23.0
Locus of failure[g]	LS	AD-LS	AD-LS	LS	LS	AD-LS	LS	LS	AD	SE

See footnotes at end of table.

APPENDIX G (Continued). PROPERTIES OF BURIED POLYMERIC MEMBRANE SPECIMENS AFTER EXPOSURE TO LEACHATE GENERATED IN SIMULATED MSW LANDFILLS

Material	Chlorosulfonated polyethylene			ELPO[k]	Ethylene propylene rubber			Neoprene		HDPE[l]
Specimen number[a]	4R-2	6R	14R	36	16	25	94	9	82	99
Type of compound[b]	TP	TP	TP	TP	XL	XL	TP	XL	XL	CX
Simulator number	2	4	3	11	5	6	11	2	12	11
Nominal thickness, mils	33	34	32-39	23	53	60	30	62.5	60	98
Exposure time, months	56	56	56	13	56	56	13	56	13	13
Analytical properties										
Volatiles, %	...	17.03	9.45	0.31	6.47	5.65	1.76	6.05	6.60	0.14
Extractables, %	1.72	3.84	4.63	6.09	30.02	22.50	73.02	10.26	12.62	...
Solvent	DMK[h]	DMK[h]	MEK[c]	MEK[c]	MEK[c]	MEK[c]	MEK[c]	DMK[h]	DMK[h]	...
Physical properties[d]										
Tensile at fabric break, ppi	...	40.6	84.3	...	...	...	...	...	...	...
Tensile at break, psi	...	2620	1720	2500[i]	1505	1640	1985	1760	1470	...
Elongation at break, %	...	200	100	570[i]	495	490	290	280	370	...
Set after break, %	...	53	26	485[i]	15	17	70	6	12	...
S-100, psi	...	1245	1720	1090[i]	295	265	1565	455	260	...
S-200, psi	...	2620	...	1170[i]	655	855	1845	1195	700	...
S-300, psi	...	...	...	1320[i]	975	1225	...	...	1190	...
Tear strength (Die C), ppi	...	...	...	410[i]	175	205	435	135	180	...
Hardness, Durometer points, 10 sec. reading	...	67A	70A	83A	47A	56A	77A	56A	49A	...
10 sec. reading	...	...	...	37D	...	...	32D	...	...	...
Puncture strength:										
Thickness of specimen, mils	...	40	40	23	58	67	26	69	71	115
Stress, lb	...	57.4	61.2	34.8	41.5	50.0	41.4	62.1	53.2	170.5
Elongation, in.	...	0.84	0.54	1.04	1.42	1.30	0.70	1.38	1.38	0.38
Seam strength										
Bonding system	Solvent 6079+ Cement L-1552	Cement 280Z	Solvent Trichloro-ethylene	Heat Factory	Solvent 374 Cement Mag 1265	XL-ADH 8800 w/tape	No seam	Cement N-100	No seam	Hot melt
Shear, ppi:	0	69.2	39.3	32.8	14.9	39.9	...	44.0	...	(m)
Locus of failure[g]	AD	SE	LS	SE	AD	AD	...	AD-LS	...	(m)
Peel:										
Average, ppi	0	16.0	3.2	24.4	0.4	7.2	...	4.0	...	(m)
Maximum, ppi	0	22.8	4.0	26.1	0.7	7.7	...	5.6	...	(m)
Locus of failure[g]	AD	AD	LS	SE	AD	AD	...	AD-LS	...	(m)

See footnotes at end of table

APPENDIX G (Continued). PROPERTIES OF BURIED POLYMERIC MEMBRANE SPECIMENS AFTER EXPOSURE TO LEACHATE GENERATED IN SIMULATED MSW LANDFILLS

Material	Polybutylene		Polyvinyl chloride							
Specimen number[a]	20	98	10	11	19-1	19-2	67	88	92A	93
Type of compound[b]	CX	CX	TP	TP	TP	TP	TP	TP	TP	TP
Simulator number	1	12	1	1	1	1	11	12	12	11
Nominal thickness, mils	8-10	6-8	34	31	20-22	20-22	21	20	22	11
Exposure time, months	56	13	56	56	56	56	13	13	13	13
Analytical properties										
Volatiles, %	0.2	0.2	6.3	2.0	0.5	...	0.7	0.7	1.3	1.7
Extractables, %	3.15	2.97	30.53	31.37	36.13	36.87	36.25	30.64	30.72	29.34
Solvent	MEK[c]	MEK[c]	CCl_4+ CH_3OH[n]	CCl_4+ CH_3OH[n]	CCl_4+ CH_3OH[n]	CCl_4+ CH_3OH[n]	CCl_4+ CH_3OH[n]	CCl_4+ CH_3OH[n]	CCl_4+ CH_3OH[n]	CCl_4+ CH_3OH[n]
Physical properties[d]										
Tensile at break, %	5500	5880	3140	2955	2765	...	2995	3590	2655	3145[i]
Elongation at break, %	365	370	330	315	340	...	3245	315	335	315[i]
Set after break, %	235	228	101	91	78	...	81	122	102	113[i]
S-100, psi	2340	2600	1825	1785	1445	...	1580	2015	1355	1805[i]
S-200, psi	...	3415	2420	2355	2020	...	2150	2730	1895	2410[i]
S-300, psi	4570	4920	2990	2885	2560	...	2755	3435	2455	3070[i]
Tear strength (Die C), ppi	480	535	450	425	345	...	360	560	420	390[i]
Hardness, Durometer points,										
10 sec. reading	88A	78A	85A	85A	75A	...	73A	78A	75A	75A
10 sec. reading	46D	50D	34D	32D	25D	...	23D	30D	26D	32D
Puncture strength:										
Thickness of specimen, mils	10	6	34	31	24	...	21	20	21	11
Stress, lb	20.0	12.0	61.2	59.7	35.9	...	5.1	34.0	33.4	18.9
Elongation, in	0.60	0.50	0.78	0.80	0.80	...	0.78	0.68	0.74	0.56
Seam strength										
Bonding system	Heat Laboratory	Heat Laboratory	Solvent THF[f]	Solvent THF[f]	Cement L1552+ Solvent 6079	Solvent THF[f]	Heat Laboratory	No seam	Solvent Factory	No seam
Shear, ppi:	>21.6	>14.9	>93.0	69.6	>41.2	>40.0	32	...	>34.8	...
Locus of failure[g]	CL	CL	LL	SE	CL	CL	LS/SE	...	CL	...
Peel:										
Average, ppi	(j)	(j)	14.0	13.6	5.6	3.1	(j)	...	8.0	...
Maximum, ppi	15.7	8.8	21.0	16.8	6.9	4.4	6.6	...	17.9	...
Locus of failure[g]	LS	LS	LS	LS	AD	LS	LS	...	LS	...

[a] Contractor's identification number. R = fabric reinforced.

[b] XL = Crosslinked or vulcanized; TP = thermoplastic; CX = partially crystalline thermoplastic.

[c] MEK = Methyl ethyl ketone.

[d] Tensile and tear properties measured in machine direction, except where otherwise noted.

[e] Vulcanized adhesive.

[f] THF = tetrahydrofuran.

[g] Locus of failure code.

AD = Failure within adhesive.
AD-AD = Failure between two coats of adhesive.
AD-LS = Failure between adhesive and liner surface.
BK = Break of liner materials outside the seam.
CL = Failure in clamped area.
DEL = Delamination of the liner material.
LS = Failure at liner surface.
OR = Failure of reinforcing fabric.
RIP = Rip outside of seam test area.
SE = Failure at seam edge.

The use of a slash indicates that the two specimens failed in different ways.

[h] DMK = Dimethyl ketone = acetone.

[i] Tested in transverse direction.

[j] Specimen failed at initial peak.

[k] ELPO = Elasticized polyolefin.

[l] HDPE - High-density polyethylene.

[m] Seam not tested but in good condition.

[n] 2:1 blend of carbon tetrachloride and methyl alcohol.

APPENDIX H. EFFECT OF IMMERSION IN MSW LEACHATE ON SELECTED PROPERTIES[a] OF POLYMERIC MEMBRANE LINERS

Material	Butyl	CPE			CSPE			ELPO
Specimen number[b]	44	12	38	86	3	6R	85	36
Type of compound[c]	XL	TP	TP	TP	TP	TP	TP	TP
Nominal thickness, mils	60	30	30	20	30	30	30	20
Analytical properties								
Volatiles, unexposed, %	0.5	0.1	0.2	0.1	0.8	0.5	0.9	0.2
After 8 mo, %	1.4	7.9	8.5	7.5	18.6	12.1	12.6	0.4
" 19 mo, %	2.6	14.4	13.3	14.8	22.8	14.9	15.9	1.5
" 31 mo, %	2.0	10.0	10.4	15.6	17.2	14.5	12.6	1.1
Physical properties								
Tensile at fabric yield[d], unexposed, ppi	...	...	...	...	...	36	...	...
After 8 mo, % ret[e]	...	...	...	...	...	75	...	...
" 19 mo, % ret	...	...	...	...	...	81	...	...
" 31 mo, % ret	...	...	...	...	...	97	...	...
Tensile at break[d], unexposed, psi	1600	2275	2095	1680	1540	1765	2200	2620
After 8 mo, % ret	93	85	90	107	113	116	83	89
" 19 mo, % ret	90	84	86	102	103	121	98	100
" 31 mo, % ret	92	84	91	104	117	131	106	101
Elongation at break[d], unexposed, %	445	410	425	475	610	250	295	665
After 8 mo, % ret	104	98	95	91	98	94	97	88
" 19 mo, % ret	99	90	86	85	89	86	78	102
" 31 mo, % ret	91	83	78	80	83	76	69	97
S-200[d], unexposed, psi	685	1330	1205	810	735	1525	1770	1020
After 8 mo, % ret	86	95	89	98	54	116	77	99
" 19 mo, % ret	90	89	90	106	46	136	108	103
" 31 mo, % ret	98	95	104	133	57	...	130	107
Tear resistance[d], unexposed, ppi	210	255	230	185	280	...	290	385
After 8 mo, % ret	90	80	78	81	59	...	74	100
" 19 mo, % ret	93	75	85	84	54	...	69	104
" 31 mo, % ret	90	69	74	81	54	...	65	139
Puncture resistance								
Max stress, unexposed, lb	39.5	47.0	47.8	20.9	25.4	32.9	47.8	26.3
After 8 mo, % ret	96	108	105	130	152	102	114	108
" 19 mo, % ret	88	104	101	127	153	140	115	97
" 31 mo, % ret	102	106	87	147	129	156	128	125
Elongation, unexposed, in.	1.18	1.04	0.86	0.91	1.16	0.60	0.86	0.97
After 8 mo, % ret	96	96	115	116	160	127	112	105
" 19 mo, % ret	93	94	109	111	154	113	98	98
" 31 mo, % ret	103	88	95	105	148	140	102	120

See footnotes at end of table

APPENDIX H (Continued). EFFECT OF IMMERSION IN MSW LEACHATE ON SELECTED PROPERTIES[a] OF POLYMERIC MEMBRANE LINERS

Material	Ethylene propylene rubber					Neoprene				Polybutylene
Specimen number[b]	8	18	41	83R	91	9	37	42R	90	98
Type of compound[c]	XL	XL	XL	TP	XL	XL	XL	XL	XL	CX
Nominal thickness, mils	60	50	20	40	35	60	70	20	35	10
Analytical properties										
Volatiles, unexposed, %	0.4	0.5	0.2	0.3	0.3	0.8	0.6	0.9	0.4	0.1
After 8 mo, %	2.9	6.0	0.3	3.0	12.7	9.0	2.1	13.3	7.2	0.1
" 19 mo, %	3.1	6.4	1.2	4.0	8.3	14.8	4.8	17.3	6.4	0.7
" 31 mo, %	2.8	6.0	0.5	4.1	9.8	8.5	4.6	15.2	9.9	0.5
Physical properties										
Tensile at fabric yield[d], unexposed, ppi	...	...	...	36	...	...	...	262	...	...
After 8 mo, % ret[e]	...	...	...	...	...	...	...	65	...	...
" 19 mo, % ret	...	...	...	89	...	...	...	79	...	...
" 31 mo, % ret	...	...	...	86	...	...	...	85	...	...
Tensile at break[d], unexposed, psi	1875	1480	3005	940	1830	2195	2365	...	2100	5605
After 8 mo, % ret	90	96	93	101	79	72	100	...	96	97
" 19 mo, % ret	90	92	94	104	89	62	100	...	95	94
" 31 mo, % ret	90	105	96	109	97	70	108	...	100	90
Elongation at break[d], unexposed, %	580	415	675	255	490	340	280	25	415	385
After 8 mo, % ret	86	88	99	112	84	87	100	160	95	96
" 19 mo, % ret	90	87	98	120	92	78	102	100	87	96
" 31 mo, % ret	88	94	94	118	99	87	129	100	78	87
S-200[d], unexposed, psi	655	755	1040	920	855	1235	1635	...	1340	3120
After 8 mo, % ret	134	111	100	98	91	79	100	...	93	101
" 19 mo, % ret	131	110	99	98	92	77	100	...	101	101
" 31 mo, % ret	134	117	105	104	98	76	99	...	115	106
Tear resistance[d], unexposed, ppi	235	180	425	..	195	215	210	...	200	370
After 8 mo, % ret	83	72	85	...	85	47	102	...	83	109
" 19 mo, % ret	87	89	95	...	100	51	114	...	88	122
" 31 mo, % ret	91	83	95	...	105	70	100	...	85	145
Puncture resistance										
Max stress, unexposed, lb	56.9	39.4	25.1	33.6	29.2	58.7	80.4	124.6	44.9	13.9
After 8 mo, % ret	97	109	100	83	94	109	113	66	110	145
" 19 mo, % ret	96	107	93	88	102	93	118	98	108	129
" 31 mo, % ret	99	116	120	89	102	101	120	109	107	132
Elongation, unexposed, in.	1.46	1.44	0.96	0.61	1.17	1.16	1.02	0.37	1.01	0.66
After 8 mo, % ret	86	82	88	84	96	104	109	95	104	112
" 19 mo, % ret	88	86	94	102	109	96	108	100	105	108
" 31 mo, % ret	95	92	114	116	103	120	134	173	92	100

See footnotes at end of table

APPENDIX H (Continued). EFFECT OF IMMERSION IN MSW LEACHATE ON SELECTED PROPERTIES[a] OF POLYMERIC MEMBRANE LINERS

Material	Polyester	LDPE	Polyvinyl chloride							PVC + pitch
Specimen number[b]	75	21	11	17	19	40	67	88	89	52
Type of compound[c]	TP	CX	TP	TP	TP	TP	TP	TP	TP	TP
Nominal thickness, mils	7	10	30	20	20	30	20	20	10	80
Analytical properties										
Volatiles, unexposed, %	0.3	0.0	0.1	0.1	0.1	0.2	0.0	0.2	0.0	0.4
After 8 mo, %	1.4	0.0	2.4	2.3	0.9	1.4	1.6	1.0	2.5	5.8
" 19 mo, %	2.1	0.2	4.4	4.4	1.9	3.6	2.6	3.0	6.4	9.3
" 31 mo, %	1.2	0.1	3.9	3.0	1.5	3.2	1.7	3.2	5.8	7.9
Physical properties										
Tensile at fabric yield[d], unexposed, ppi	...	...	...	...	...	...	...	...	...	...
After 8 mo, % ret[e]	...	...	...	...	...	...	...	...	...	...
" 19 mo, % ret	...	...	...	...	...	...	...	...	...	...
" 31 mo, % ret	...	...	...	...	...	...	...	...	...	...
Tensile at break[d], unexposed, psi	6770	2145	2960	2580	2520	2790	2895	3155	3400	1095
After 8 mo, % ret	107	139	95	95	103	91	95	93	99	92
" 19 mo, % ret	88	114	92	102	103	92	96	93	96	90
" 31 mo, % ret	85	135	107	109	107	96	93	100	93	102
Elongation at break[d], unexposed, %	575	505	335	280	335	395	400	330	320	165
After 8 mo, % ret	106	123	110	123	124	99	103	106	103	118
" 19 mo, % ret	93	107	113	129	119	105	100	105	105	103
" 31 mo, % ret	88	117	104	120	99	90	81	94	94	91
S-200[d], unexposed, psi	2735	1260	2125	1965	1740	1720	1705	2400	2455	...
After 8 mo, % ret	102	106	87	80	89	91	92	79	96	...
" 19 mo, % ret	98	102	85	84	94	91	105	88	95	...
" 31 mo, % ret	100	106	98	94	112	104	117	101	105	...
Tear resistance[d] unexposed, ppi	845	390	375	335	285	335	320	465	400	250
After 8 mo, % ret	81	99	95	91	96	88	89	73	83	80
" 19 mo, % ret	91	100	97	91	105	91	108	82	96	86
" 31 mo, % ret	101	101	104	84	114	94	116	92	106	92
Puncture resistance										
Max stress, unexposed lb	29.9	13.9	37.4	25.8	24.0	43.1	27.8	28.6	17.0	62.3
After 8 mo, % ret	66	114	117	126	103	106	107	100	118	86
" 19 mo, % ret	81	117	120	126	96	93	111	119	103	106
" 31 mo, % ret	75	106	143	124	122	103	142	128	146	120
Elongation, unexposed, in.	1.30	0.76	0.63	0.69	0.71	0.72	0.68	0.56	0.48	0.49
After 8 mo, % ret	85	130	110	113	90	111	107	107	146	104
" 19 mo, % ret	105	138	113	128	97	103	109	132	125	106
" 31 mo, % ret	79	103	119	126	97	117	131	130	156	114

[a] Analytical properties: volatiles, percent loss of weight after two hours at 105°C. Physical properties: tensile, elongation, and modulus, ASTM D412; tear resistance, ASTM D624; puncture resistance, FTMS 101B, Method 2065.

[b] Contractor's identification number. R = fabric-reinforced.

[c] XL = crosslinked; TP = thermoplastic; CX = partially crystalline.

[d] Data based on average of two directions.

[e] Percent retention.

APPENDIX I

EFFECT OF EXPOSURE OF SEAMS TO MSW LEACHATE UPON THE SEAM STRENGTH OF FLEXIBLE MEMBRANE LINERS

		Adhesion system			Unexposed seams				After exposure period I						After exposure period II					
					Peel test		Shear test			Peel test			Shear, ppi			Peel test			Shear test	
Polymer	Seam no.	Type^a	Fab. site^b	Detail^c	Avg. ppi	Failure^d	Avg. ppi	Failure^d	Time, mos.	Avg. ppi	Max. ppi	Failure^d	ppi.	Failure^d	Time, mos.	Avg. ppi	Max. ppi	Failure^d	ppi	Failure^c
Butyl rubber	7-PR	XL-A	Lab.	8800+cold seal tape+ lap sealant	3.8	AD-LS^e	30	AD-LS^e	12	2.9	4.0	AD-LS	42	AD-LS	56	3.4	3.8	AD-LS	17	AD-LS
	7	"	"	8800+cold seal tape	3.8	AD-LS^e	30	AD-LS^e	"	3.7	"	"	37.3	"	"	3.0	4.2	AD-LS	40	AD-LS
	22	"	"	"	6.5	AD-LS^e	32.5	AD-LS^e	"	5.1	7.2	AD	27.3	AD-LS	"	8.4	9.1	AD	34	AD
	24	"	"	"	3.3	AD-LS^e	41.5	AD-LS^e	"	2.8	3.4	AD-LS	37.2	"	"	4.8	6.8	AD	46	AD
Chlorinated polyethylene (CPE)	12-1	Cmt.	Lab.	SC-1556	2.0	AD-LS	38.6	AD-LS	"	2.2	3.7	AD-LS	46.0	AD-LS	"	1.4	2.6	AD-LS	34	AD
	12-PR	Solv.	"	50 toluene: 50 THF	10	LS	57	BK/LS	"	5.2	6.7	LS	>35	BK/CL	"	2.9	4.5	LS	17	LS
	12-2	"	"	"	10	LS	57	"	"	2.4	3.1	LS	56.0	LS	"	2.0	2.6	LS	...	...
	12-3	"	"	60 TCE:40 toluene	3.9	LS	50	"	"	3.0	4.4	LS	51.0	LS	"	1.8	2.5	LS	40	LS
	12-4	Cmt.	"	SC-1554	7	AD-LS	48	AD-LS	"	8.3	11.6	AD	48.1	AD-LS	"	10.0	11.7	AD	58	SE
	13R^f-1	"	"	SC-1556	10	AD-LS	>200	BK	"	3.8	5.2	AD-LS	>122	BK	"	0.4	0.8	AD-LS	56	AD-LS
	13R^f-2	Solv.	"	50 toluene:50 THF	10	LS	>218	BK/LS	"	2.5	3.7	LS	>58	OR	"	4.0	4.4	LS	64	DEL
	13R^f-3	"	"	60 TCE:40 toluene	2	LS	127	LS	"	1.2	1.9	LS	43	LS	"	1.2	1.9	LS	48	LS
	13R^f-4	Cmt.	"	SC-1554	6.8	AD-LS	>170	BK	"	5.8	5.9	AD-LS	>58	BK	"	4.8	7.3	AD-LS	78	DEL
	23-1	"	"	SC-1556	1.0	AD-LS	>30	BK	"	1.0	1.7	AD-LS	...	...	"	0.4	0.6	AD-LS	16	AD-LS
	23-2	Solv.	"	50 toluene:50 THF	9.5	LS	>27	BK	"	4.8	6.6	LS	>31	BK	"	4.6	5.3	LS	>23	CL
	23-3	"	"	60 TCE:40 toluene	6.5	LS	>30	BK	"	2.7	3.2	LS	>33	BK	"	2.6	3.0	LS	>21	CL
	23-4	Cmt.	"	SC-1554	6.4	AD-LS	>30	BK	"	5.4	6.6	AD-LS	>34	BK	"	5.4	6.6	AD-LS	>23	CL
	38	Heat	"		...	...	...	...	13	(h)	5.4	LS	20	LS	...	...	...	...	...	...
Chlorosulfonated polyethylene (CSPE)	3-1	Heat	Fac.		>21	BK	>26	BK	...	...	...	...	...		56	11.1	13.3	LS	32.3	SE
	3-2	Cmt.	Lab.	Solv 6079+Cmt L1552	2	AD-LS	17	AD-LS	12	2.6	3.6	AD	18.0	AD	"	2.3	3.9	AD	...	...
	4R^f-1	Heat	Fac.		>24	DEL	>61	BK	"	...	>21	RIP	>26	BK	"	...	23.0	SE	48/30	OR/RIP
	4R^f-2	Cmt.	Lab.	Solv 6079+Cmt L1552	0	AD-AD	0	AD-AD	"	0	0	AD	0	AD	"	0	0	AD	0	AD
	6R^f	"	"	280Z	>30	BK/DEL	>50	BK	"	17	26	AD	>64	BK	"	16.0	22.8	AD	69	SE
	6R-PR	"	"	"	>30	BK/DEL	>50	BK	"	3.4	5.2	AD	40.2	AD	"	1.8	3.2	AD-LS	10	AD-LS
	14R^f	Solv.	"	Trichloroethylene	1	LS	50.5	LS	"	0.6	1.3	LS	16.0	LS	"	3.2	4.0	LS	39.3	LS
Elasticized polyolefin	36	Heat	Fac.		..	...	...	...	13	24.4	26.1	SE	32.8	SE	...	...	...	...	...	...
Ethylene propylene rubber	8	XL-A	Lab.	8800+cold seal tape	4.5	AD^e	37	AD^e	12	7.3	7.4	AD	45.0	AD	43	8.6	9.2	AD	60.0	AD-LS
	18	Cmt.	"	Solv 374+Cmt MAG 1265	2.5	AD-LS	14.6	AD-LS	"	2.1	2.4	AD-LS	16.0	AD-LS	56	0.4	0.7	AD	15	AD
	18-PR	"	Fac.	Solv 374+Cmt MAG 1265	5.4	AD-LS	44.5	AD/BK	"	2.0	2.4	AD-LS	24.3	AD-LS	"	7.1	7.6	AD	18	AD
	25	XL-A	Lab.	8880+cold seal tape	6.8	AD^e	33	AD^e	"	8.0	8.7	AD-LS	42.3	AD-LS	"	7.2	7.7	AD	40	AD
	26	"	"	"	6.0	AD^e	45.5	AD^e	"	5.6	6.1	AD	41.3	AD	43	7.4	8.4	AD	23.4	AD-LS
Neoprene	9	Cmt.	Lab.	N-100	12.4	AD-LS	85	AD	"	4.9	6.3	AD-LS	62.3	AD-LS	56	4.0	5.6	AD-LS	44.0	AD-LS
Polybutylene	20	Heat	Lab.		13.0	LS	>30	None	"	(h)	11.8	LS	(g)	...	"	(h)	15.7	LS	>22	CL
	98	"	"		...	...	...	...	13	(h)	8.8	LS	>15	CL	...	...	...	...	...	...

Continued

APPENDIX I

EFFECT OF EXPOSURE OF SEAMS TO MSW LEACHATE UPON THE SEAM STRENGTH OF FLEXIBLE MEMBRANE LINERS (Continued)

		Adhesion system			Unexposed seams				After exposure period I						After exposure period II					
					Peel test		Shear test			Peel test			Shear, ppi			Peel test			Shear test	
Polymer	Seam no.	Type[a]	Fab. site[b]	Detail[c]	Avg. ppi	Fail-ure[d]	Avg. ppi	Fail-ure[d]	Time, mos.	Avg. ppi	Max. ppi	Fail-ure[d]	ppi.	Fail-ure[d]	Time, mos.	Avg. ppi	Max. ppi	Fail-ure[d]	ppi	Fail-ure[d]
Polyethylene-low density	21-PR	Heat	Lab		15.6	LS	>20	None	12	(h)	...	...	>11	CL	56	(h)	12	SE	11	SE
Polyvinyl chloride	10	Solv.	Lab.	THF	13.3	LS	>65	BK	"	10.4	14.3	LS	>82	BK	"	14.0	21.0	LS	>93	CL
	11	Solv.	Lab.	THF	14.6	LS	>54	BK	"	10.2	14.3	LS	>65	BK	"	13.6	16.8	LS	70	SE
	15	Cmt.	Fac.	Solv. 6079+Cmt L1552	5.0	AD-LS	>20	BK	"	2.1	2.6	AD	>9.5	BK	43	3.0	3.8	AD	>18	CL
	17-PR	"	"	"	4.0	AD-AD	27.2	AD/BK	"	5.1	5.6	AD-LS	>26	CL	56	5.6	7.5	AD	>22	BK
	17	"	"	"	2.0	AD-AD	37.2	AD-AD	"	2.2	2.9	AD	>31	BK	43	3.8	5.0	AD	>35	CL
	19-1	"	Lab.	"	5.9	AD-AD	>40	BK	"	4.9	6.0	AD	>36	BK	56	5.6	6.9	AD	>41	CL
	19-2	"	"	THF	8.6	LS	>36	BK	"	3.0	6.5	LS	...	...	"	3.1	4.4	LS	>40	...
	67	Heat	"		...	...	...	...	13	(h)	6.6	LS	32	LS/SE	...	...	...	...	...	...
	92-A	Solv.	Fac.	No details provided	...	...	...	...	"	8.0	18	LS	>35	CL	...	...	...	...	...	...

[a] Type of adhesive system:
Cmt. = cement
Solv. = solvent
XL-A = vulcanizing adhesive.

[b] Type of fabrication site:
Fac. = factory
Lab. = laboratory

[c] Detail:
TCE = Trichloroethane.
THF = Tetrahydrofouran.

[d] Failure code:
AD = Failure within adhesive.
AD-AD = Failure between two coats of adhesive.
AD-LS = Failure between adhesive and liner surface.
BK = Break of liner materials outside of the seam.
CL = Failure in clamped area.
DEL = Delamination of the liner material.
LS = Failure at liner surface.
OR = Failure of reinforcing fabric.
RIP = Rip outside of seam test area.
SE = Failure at seam edge.
The use of a slash indicates that the two specimens failed in different ways.

[e] Specimen tacky.

[f] R = Fabric reinforced

[g] Tab end too small to pull specimen.

[h] No average: seam failed at initial peak.